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MACHINE GRADING OF ITALIAN STRUCTURAL TIMBER: PRELIMINARY RESULTS ON DIFFERENT WOOD SPECIES

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ABSTRACT: Italian forests are characterized by a high number of species, as a result of the great variability of climatic conditions, soil, altitude and exposure. Therefore there are many wooden species, potentially suitable for several uses, including structural. Currently, the structural timber used in Italy is mostly imported, partly because the technological characteristics of the national timber are little known. In the project supported by the EIM (Ente Italiano per la Montagna) and PAT (Provincia Autonoma di Trento), machine grading and bending tests were performed over 6 different wooden species (spruce, fir, Douglas fir, larch, Corsican pine, chestnut). About 1,600 rectangular cross section beams (2 different cross section sizes per species) have been evaluated with a grading machine that combines the determination of dynamic modulus of elasticity with X-ray imaging analysis (GoldenEye-706), and then tested in the laboratory according to EN 408. The results show first of all the good mechanical performances of some Italian wooden species, in particular Douglas fir and pine. The dynamic modulus of elasticity was generally well correlated with the values determined by bending test. Moreover, the efficiency of the grading, determined according to the optimum grade as required by EN 14081-2, was variable depending on the species, and therefore its specific wood properties. Although the number of specimens analyzed is not large enough to validate a procedure for initial type testing, the results obtained are interesting from the perspective of the Italian timber promotion.

KEYWORDS: Strength grading, Non-destructive measurement, Bending test, Timber strength, X-ray analysis

1 INTRODUCTION

Italian forests are characterized by a high number of tree species, as a result of the great variability of climatic conditions (both continental and Mediterranean climate), soil, altitude and exposure. Therefore, there are many timber species, potentially suitable for several uses, including structural one.

At the same time, Italian wood market is very active and the building industry shows a high growth potential: the number of timber structures is rapidly expanding, especially by public bodies, but also private owners are more and more interested in using timber. Traumatic events such as the recent earthquake in L'Aquila (April 2009), as well as the increasing attention to living comfort, the growing interest to save energy and to reduce the human impact on the environment, finally spread again the "culture" of timber structures in Italy too.

At present, the structural timber used in Italy is mostly imported, because, among other reasons, the technological characteristics of national timber are little known or not recognized. Some synthetic data summarize the "wood economy" in Italy:

- Italy is one of the major importers of wooden products for construction (the fifth in the world), that come mainly from Austria, China and Germany [1];
- during 2008, Italy imported about 1,752,000 cubic meter of logs and sawn timber of softwoods and 1,662,000 cubic meter of hardwoods [2], against a national timber production of 1,380,031 cubic meter of softwoods and 1,120,121 cubic meter of hardwoods (data 2007, www.istat.it);
- in 2007, Italy became the biggest consumer of structural glulam in Europe (www.euwid.de);
- the 30% of imported timber products is glulam [1];
- the 24% of employees in Italian wood industry works in products for structural applications [3].

On the other hand, timber elements used for structural purposes have to meet the requirements of the Construction Products Directive (Council Directive 89/106/EEC). The compliance with the Directive is

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manifested visibly by the appearance of the CE mark, which is going to be compulsory in Europe. To get the CE mark each timber piece has to be strength graded according to the indications of the standard EN 14081 [4].

Strength grading requires the measurement and the observation of some timber characteristics in order to predict its mechanical performance. Indeed, the only way to know exactly the strength of a timber piece is to load it to failure, making it unusable. Therefore, indirect and non-destructive methods have to be applied. But, because of the timber properties variability, the statistical approach provided by the standard [4] and in order to reduce the uncertainty of indirect strength prediction, numerous experimental data from different species, various cross sections and geographical origin are needed [5].

For these reasons, CNR-IVALSA started a research program to promote Italian timber for structural uses, by characterizing several wood species (from physical and mechanical point of view) and testing the efficiency of visual and machine grading methods. In this paper a part of the results of the study are reported.

2 MATERIALS AND METHODS

Altogether, 1641 structural size timber elements were tested. The species included in the study were 5 softwoods and 1 hardwood: larch (*Larix decidua* Mill.) and spruce (*Picea abies* Karts.) from the North of Italy; fir (*Abies alba* Mill.) and Douglas fir (*Pseudotsuga menziesii* Franco) from central Italy; Corsican pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) and chestnut (*Castanea sativa* Mill.) from southern Italy. For each species 2 cross sections, representing the timber sizes and quality commonly presented in the Italian structural timber market, and 2-3 provenances were sampled. The number of timber elements grouped by species and size is reported in Table 1.

Table 1: *Number of tested timber elements for each species and cross section in mm (symbols explained in Table 2)*

Cross section	ABAL	PCAB	LADC	PNNL	PSMN	CTST
80x80						130
50x100						170
70x110	173			155	198	
50x120		139	118			
80x150	109	139	108	99	103	
Total	282	278	226	254	301	300

After dried to an average moisture content of 11-12%, each specimen was machine graded with GoldenEye-706 by MiCROTEC Srl. The machine combines the vibration measurement and the X-ray scanning [6, 7]; the grading parameters measured are dynamic modulus of elasticity, density and knot characteristics (size and position over the entire length of the piece). Based on these measures, the machine returns the Indicating Properties (IP) for modulus of elasticity (IP_{MOE}), density (IP_{DEN}), knots (IP_{KN}) and, combined in a mathematical model, for bending strength (IP_{MOR}).

Edgewise bending tests were then carried out for each timber piece at CNR-IVALSA laboratories (spruce and larch samples in Trento, the others in Florence) in accordance with EN 408 [8] and the adjustments for strength and stiffness properties calculations were made according to EN 384 [9]. In the following analysis the local MOE was used (measured according to the paragraph 9 of EN 408 [8]).

All the symbols used in the following text, tables and graphs are explained in Table 2.

Table 2: *Symbols used in the text, tables and graphs to indicate the timber species and the properties studied.*

	Symbol
Timber species	
Abies alba	ABAL
Picea abies	PCAB
Larix deciduas	LADC
Pinus nigra subsp. *laricio*	PNNL
Pseudotsuga menziesii	PSMN
Castanea sativa	CTST
Machine Indicating Properties	
Predicted strength	IP_{MOR}
Dynamic modulus of elasticity	IP_{MOE}
Wood density	IP_{DEN}
Knots	IP_{KN}
Laboratory Properties	
Modulus of rupture	MOR_{LAB}
Modulus of elasticity	MOE_{LAB}
Wood density	DEN_{LAB}

The quality of Italian structural timber was evaluated by the calculation of the optimum grade, as described by prEN 14081-2 [10], based on the laboratory results. In optimum grading the pieces are assigned into the highest possible grade as it would be done by a fictitious perfect grading machine.

In Europe the strength classes are divided in C-classes for softwood and D-classes for hardwood. The requested values of strength, stiffness and density for the assignment to the C- and D-classes are provided by EN 338 [11]. For the optimum grade elaboration, the values were modified by k_v-factor (dividing strength by 1.12 for classes $\leq$ C30 and D30) and 95%-factor (stiffness) as indicated in prEN 14081-2 [10] (Table 3 and Table 4).

The machine efficiency was verified by means of the regression analysis (coefficient of determination) calculated between the properties values from laboratory tests (MOR_{LAB}, MOE_{LAB}, DEN_{LAB}) and the same properties measured by the machine (IP_{MOR}, IP_{MOE}, IP_{DEN}). In the same way, the machine grading efficiency was checked by the coefficient of determination between the strength values from bending test (MOR_{LAB}) and machine indicating properties (IP_{MOE}, IP_{DEN} and IP_{KN}).

***Table 3:** Required values for strength (MOR), stiffness (MOE) and density (DEN) for some C-classes defined in EN 338 and respective modified values (MOR_{mod}; MOE_{mod})*

Class	MOR (N/mm^2)	**MOR$_{mod}$** (N/mm^2)	MOE (N/mm^2)	**MOE$_{mod}$** (N/mm^2)	DEN (kg/m^3)
C16	16	14.3	8 000	7 600	310
C18	18	16.1	9 000	8 550	320
C24	24	21.4	11 000	10 450	350
C27	27	24.1	11 500	10 925	370
C30	30	26.8	12 000	11 400	380
C35	35	35.0	13 000	12 350	400
C40	40	40.0	14 000	13 300	420

***Table 4:** Required values for strength (MOR), stiffness (MOE) and density (DEN) for D-classes defined in EN 338 and respective modified values (MOR_{mod}; MOE_{mod})*

Class	MOR (N/mm^2)	**MOR$_{mod}$** (N/mm^2)	MOE (N/mm^2)	**MOE$_{mod}$** (N/mm^2)	DEN (kg/m^3)
D18	18	16.1	9 500	9 025	475
D24	24	21.4	10 000	9 500	485
D30	30	26.8	11 000	10 450	530
D35	35	35.0	12 000	11 400	540
D40	40	40.0	13 000	12 350	550
D50	50	50.0	14 000	13 300	620
D60	60	60.0	17 000	16 150	700
D70	70	70.0	20 000	19 000	900

3 RESULTS

The mean values and the coefficients of variation of strength, stiffness and wood density for each species are reported in Table 5.

Very interesting were the strength and stiffness values of Douglas fir: they were the highest among the softwoods studied, while its wood density on average was lower than that of pine and larch. Corsican pine, moreover, showed higher mean strength values than fir and spruce, comparable to larch strength properties.

The only hardwood included in the study, chestnut, had the highest values of bending properties and wood density and the lowest coefficients of variation.

The good mechanical properties of the studied species were confirmed by the yields of the optimum grade calculated for different grade combinations for softwoods (Table 5) and singularly by strength class for chestnut (Table 6). Among the softwoods, larch and Douglas fir showed the largest numbers of pieces in the highest grades in all grade combinations; spruce, primarily, and fir, secondly, the lowest.

Chestnut reached very high yields in the lowest classes, but still very good percentages till D35-D40. When the optimum grade was performed ignoring wood density as grading requirement, the yields were much higher and the mean density values in each class were quite similar each other.

***Table 5:** Mean value and coefficient of variation (CV) for strength (MOR_{LAB}), stiffness (MOE_{LAB}) and density (DEN_{LAB}) of each species*

Species	MOR$_{LAB}$		MOE$_{LAB}$		DEN$_{LAB}$	
	mean (N/mm^2)	CV (%)	mean (N/mm^2)	CV (%)	mean (kg/m^3)	CV (%)
ABAL	41.0	34	11500	21	434	9
PCAB	41.5	31	10500	24	409	8
LADC	46.9	38	11800	24	551	9
PNNL	44.2	35	10700	30	519	11
PSMN	48.9	39	12800	24	492	11
CTST	49.4	26	13200	18	583	8

***Table 6:** Optimum grade – yield (%) for different grade combinations for softwood species*

Grade combination	ABAL	PCAB	LADC	PNNL	PSMN
C24	97.5	98.6	99.1	99.2	98.7
REJ	2.5	1.4	0.9	0.8	1.3
C30	89.4	75.5	92.9	85.4	91.4
C18	9.2	15.1	-	-	7.6
REJ	1.4	9.4	7.1	14.6	1.0
C35	59.6	47.5	75.7	63.0	73.4
C24	28.4	21.6	12.4	8.7	18.6
REJ	12.1	30.9	11.9	28.3	8.0
C35	59.6	47.5	75.7	63.0	73.4
C27	20.9	14.7	9.3	-	13.0
C18	17.4	27.0	-	26.8	12.6
REJ	2.1	10.8	15.0	10.2	1.0
C40	34.4	22.7	55.3	46.5	66.4
C30	41.1	37.4	15.9	-	15.9
C18	24.1	30.9	27.9	51.2	16.9
REJ	0.4	9.0	0.9	2.4	0.7

***Table 7:** Optimum grade – yield, considering and ignoring wood density as grade requirement, for each D-class for chestnut*

Class	Considering density		Ignoring density	
	DEN (kg/m^3)	Yield (%)	DEN (kg/m^3)	Yield (%)
D18	507	100	507	100
D24	507	100	507	100
D30	532	91	508	100
D35	540	81	513	92
D40	550	66	512	82
D50	621	11	524	48
D60	-	0	525	12
D70	-	0	-	0

***Table 8:** Coefficients of determination (R^2) of regression analysis between laboratory and machine values of strength, MOE and density (symbols explained in Table 2)*

Species	MOR_{LAB} *vs.* IP_{MOR}	MOE_{LAB} *vs.* IP_{MOE}	DEN_{LAB} *vs.* IP_{DEN}
ABAL	0.529	0.736	0.777
PCAB	0.573	0.893	0.925
LADC	0.645	0.800	0.938
PNNL	0.691	0.826	0.858
PSMN	0.656	0.736	0.833
CTST	0.184	0.535	0.768

***Table 9:** Coefficients of determination (R^2) of regression analysis between laboratory values of strength and machine values of MOE, density and knots (symbols explained in Table 2)*

Species	MOR_{LAB} *vs.* IP_{MOE}	MOR_{LAB} *vs.* IP_{DEN}	MOR_{LAB} *vs.* IP_{KN}
ABAL	0.447	0.249	0.345
PCAB	0.484	0.254	0.342
LADC	0.492	0.104	0.446
PNNL	0.584	0.225	0.493
PSMN	0.575	0.422	0.450
CTST	0.140	0.043	0.083

The coefficients of determination, as results of the regression analysis between laboratory and machine measurements, are showed in Table 8 and the relative scatter plots in Figures 1-3. The coefficients differed greatly by species and were particularly low for chestnut (strength and stiffness). For softwoods the machine measurement efficiency was overall quite high.

The coefficients of determination and relative scatter plots of timber strength measured in laboratory by bending tests *vs.* the different machine Indicating Properties are showed in the Table 9 and Figures 4-6. Again, the coefficients of determination differed by species and were always very low for chestnut. However, for all the species studied, the best predictor of timber strength was the modulus of elasticity, followed by knot parameter and wood density. For softwoods, about 45-58% of the strength variation could be explained by dynamic MOE; while the portion of variation explained by density varied from 10 to 42%, and from 34 to 49% for knot parameter.

For chestnut, the values of the coefficient of determination were near zero both for density and knots and very low (0.14) for stiffness (Table 9).

As expected, the relationships between strength and stiffness and between strength and density were positive (Figure 4-5), while correlations between strength and knots were negative (Figure 6).

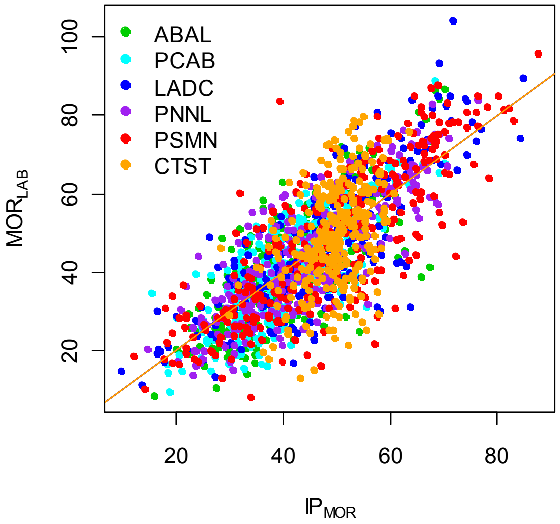

***Figure 1:** Scatter plot for laboratory strength values (MOR_{LAB}) vs. strength calculated by the machine (IP_{MOR})*

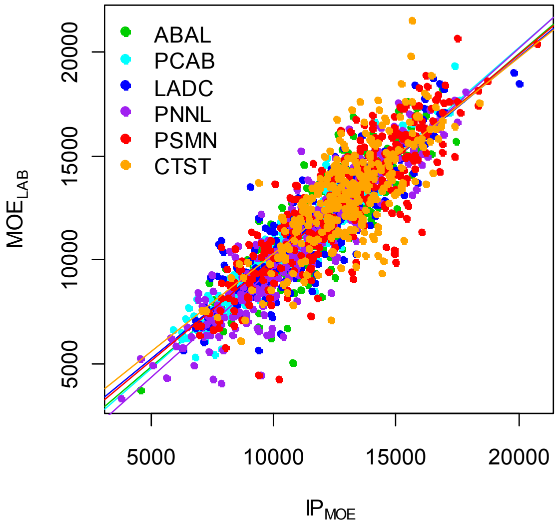

***Figure 2:** Scatter plot for laboratory stiffness values (MOE_{LAB}) vs. stiffness measured by the machine (IP_{MOE})*

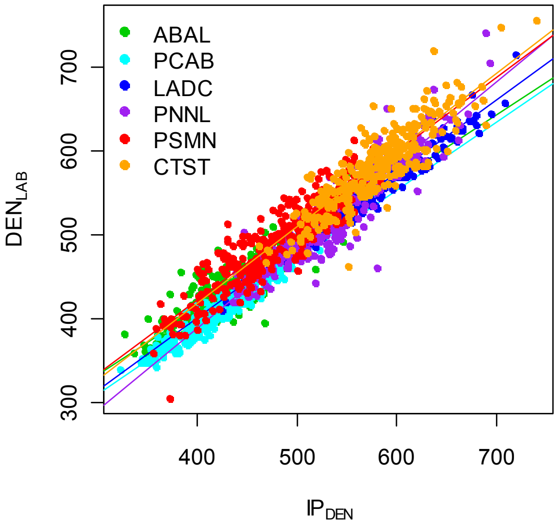

Figure 3: *Scatter plot for laboratory density values (DEN_{LAB}) vs. density measured by the machine (IP_{DEN})*

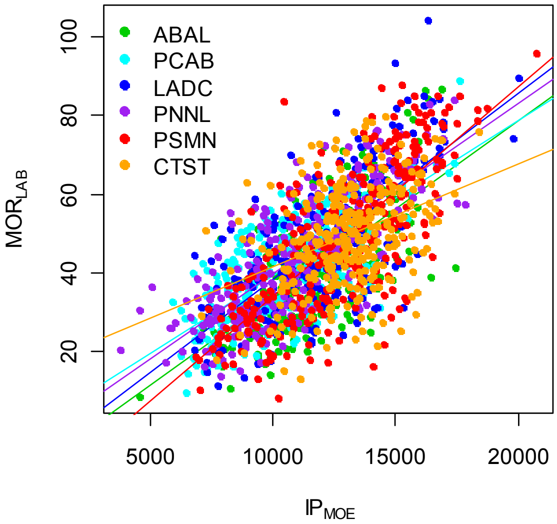

Figure 4: *Scatter plot for laboratory strength values (MOR_{LAB}) vs. stiffness measured by the machine (IP_{MOE})*

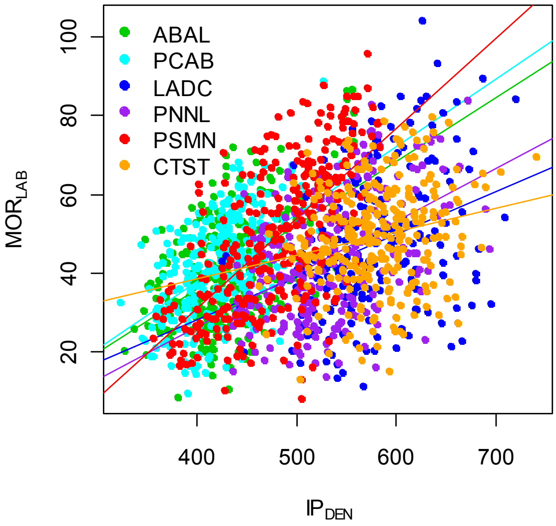

Figure 5: *Scatter plot for laboratory strength values (MOR_{LAB}) vs. density measured by the machine (IP_{DEN})*

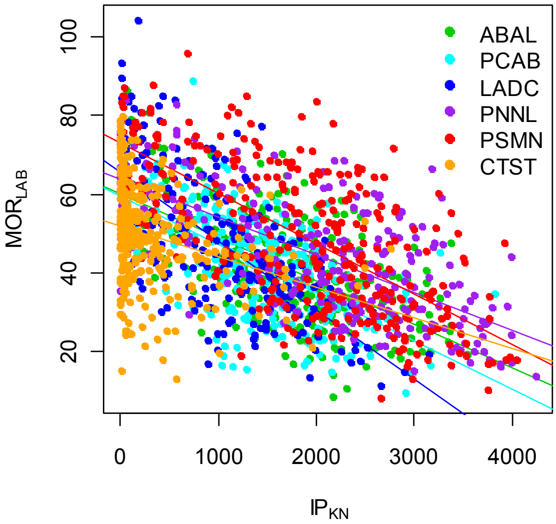

Figure 6: *Scatter plot for laboratory strength values (MOR_{LAB}) vs. knots measured by the machine (IP_{KN})*

4 DISCUSSIONS

The descriptive statistics of bending strength properties and the optimum grade yields revealed the good performances of the Italian structural timber. In particular Douglas fir and Corsican pine, although less known and used than fir and spruce, showed to be entirely suitable for structural purposes.

In the optimum grade the yields were particularly high for larch, Douglas fir and Corsican pine, among softwoods, for all the different grade combinations.

As strength grading is based on statistical properties, it depends strongly on how many and which grades are considered simultaneously [12]. It is not always possible to assign pieces to the lower strength classes, as in optimum grading the pieces are assigned to the highest possible grade and the remaining pieces for some grade combinations don’t fulfil the requirements of the next lower grade.

The optimum grade for chestnut was performed singularly for each strength class in order to verify the yield in the highest possible class. The comparison between the including- and ignoring-density calculations of the optimum grade yields showed the “weakness” of density to predict chestnut timber strength (as revealed by regression analysis too). The mean density values of each strength class were rather homogeneous and, for the high strength classes, they were quite lower than the standard requirements. Indeed density is the limiting factor in strength grading of chestnut for the higher strength classes. As strength and stiffness are typically seen as more important grade determining properties, it could be considered to lower the density requirements.

With regard to the machine grading of Italian structural timber, the comparison between destructive and non-destructive measurements showed a very high prediction power of the machine for all strength, stiffness and density of timber. The property most reliably determined by the machine was the wood density (measured by X-Ray scanning of the timber element), followed by modulus of elasticity (dynamic modulus of elasticity obtained measuring the natural frequency in longitudinal stress wave vibration), and strength (calculated combining stiffness, wood density and knot parameters by a mathematical model). Similar results were found out for GoldenEye-706 in previous works on Scots pine from Poland [12], spruce and fir from Central Europe [7], spruce and pine from Northern Europe [13].

The coefficients of determination for laboratory *vs.* machine measurements were quite similar for all the softwood studied, while the machine efficiency in predicting chestnut mechanical strength and stiffness resulted to be quite lower. In particular, the identification and, therefore the measurement, of knots in chestnut timber resulted quite difficult: in fact the localization of knots by the X-Ray scanning works on the difference between knot and normal wood density, as knots for softwood species have a factor of two higher densities than clear wood. This difference is lower in hardwood timber, so that to reduce the efficiency in measuring knot area [6].

The regression analysis between bending strength and machine Indicating Properties showed the dynamic MOE as the best single predictor of timber strength for all the species included in the work. The same result was found out in previous studies both in softwoods [13] and hardwoods [5, 14].

Wood density and knots seems to be weak predictors of strength if used independently. Density, in particular, is highly and positively correlated with mechanical properties of clear wood (small samples free of defect), but the correlation decreases deeply to 16-40% for structural size softwood [15].

The correlation between density and strength was particularly low for chestnut (almost no correlation). Similar results were reported previously for hardwoods [5], indicating the difficulties in using wood density to grade and predict structural timber strength for hardwoods.

Knots, on the other side, were slightly better correlated with structural timber strength then density, but the values of the coefficients of determination were still moderate. It is important to notice, however, that the correlation coefficients between strength and knot parameter measured during the visual strength grading (data not shown) were still lower then that obtained by the machine, indicating a higher efficiency of machine knot parameter as regard timber strength prediction.

The prediction of timber strength greatly improved when the three machine Indicating Properties (dynamic MOE, density and knots) were combined to calculate the IP_{MOR}. In this case, the coefficients of determination were the highest [6, 7, 13, 14].

The efficiency in both timber property determination and machine strength grading differed according to the tested species. Spruce and fir showed very similar mechanical performance and comparable grading results, such as to allow putting them in a single group for the further strength grading rules. Chestnut, on the contrary, turned out to be very difficult to grade because of the complications in measuring some timber characteristics (mainly knots) and the general inefficiency of the grading. Only a weak correlation could be detected between strength and dynamic modulus of elasticity, but no relationship with density and knots was found, making the indirect prediction of chestnut timber strength difficult. Grouping of species may be an option in this case [5].

5 CONCLUSIONS

Although the number of specimens analyzed was not large enough to validate a procedure for initial type testing, the results obtained were interesting from the perspective of the Italian timber promotion.

All the species studied showed very good strength properties and proved to be suitable to structural use. In particular, Douglas fir and Corsican pine among softwoods and chestnut, the only hardwood included in the study, stood out for their good mechanical performances.

The measurement of timber properties by the GoldenEye-706 confirmed to be effective for the Italian structural timber as well. The efficiency was quite high for the softwoods, but much lower for chestnut because of the general difficulties in determining some hardwood properties (i.e. knots).

The machine grading was overall rather efficient. Generally, knots and density, if considered individually, were weakly correlated with timber strength, although these parameters are used normally in visual timber strength grading. The best prediction of timber strength was obtained by combining dynamic modulus of elasticity measurements with knots and density determinations.

Concerning both strength properties and machine grading, differences among the various species were noticed. Fir and spruce were very similar, such as to suggest to group them for grading purposes; while chestnut showed very good mechanical properties, but seemed to be very difficult to grade.

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