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"Strength grading of structural timber by non-destructive methods: a case study in Italy".

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Summary

Procedures used for determining the characteristic values of mechanical properties and densities of spruce timber from Fiemme Valley -Dolomites, Italy- to prove a possible use in load-bearing structures, according to Eurocode 5 and its supporting CEN Standards, are firstly illustrated. Results of the visual grading according to DIN 4074/1989 are therefore given. Afterwards, several possible and easy to handle non-destructive techniques suitable for an optimised machine grading are illustrated with specific consideration to their different economic yield.

1.Introduction

The European Design Code Eurocode 5 -"Timber Structures", ENV 1995 - has recently been introduced in the European countries for an experimental period of time. ENV 1995 requires the knowledge of the strength profile of timbers to be used for structural purposes. Therefore strength grading of structural timbers is nowadays really decisive if one wants to improve the use of timber in civil engineering structures.
The case studied by the Authors considers the Spruce timber (*Picea abies*) of the Fiemme Valley - in the east-northern part of Italy, near Dolomites - where the tradition of wood utilisation in buildings dates back to millemniums.
The owner of the forest is Comunita' Generale di Fiemme, also called Magnificent, that is a Community within the people of the Valley that dates to the Middle Age, and that has looked after its own forests and has garanteed their preservation for centuries by optimal logging and reforestation. Nowadays, nevertheless, the Fiemme Spruce Timber is not used in structures. In line with the last years market trend specific products for makers of windows, doors and furnitures have been obtained.
But now in Italy with the recent increasing demand of old buildings renovation and preservation and the contemporary introduction of the Eurocode 5, time is possibly ready to go back to the utilisation of such timber in structures.
The objectives of the research performed by the Authors are therefore to qualify the Fiemme Spruce according to Eurocode 5.

2.Determination of characteristic values of mechanical properties

2.1 Sampling

The forest is 10,000 hectars wide and Spruce is the most frequent timber species, 80% of the total surface, while Silver fir and Larch cover the rest. Trees grow in a closed wood , solid ground, altitude between 1,500 and 1,800 meters above sea level. The forest is divided into 8 logging zones. The yearly logging is about 40,000 m^3. Period of rotation

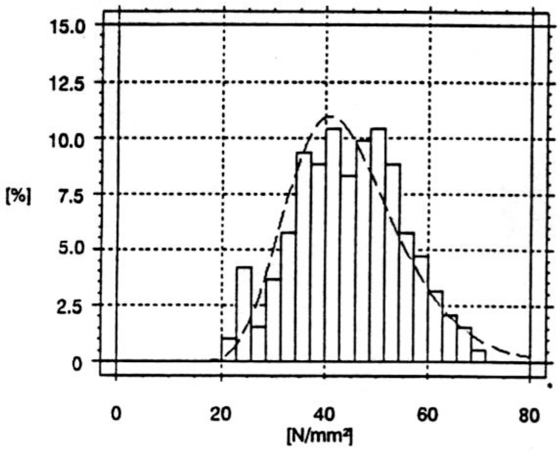
is 150 years and trees are logged when their trunk diameter at 1.30 m above the ground is about 47-48 cm. All the obtained trunks, 450 cm long, are therefore transported to the Comunita's sawmill in Ziano di Fiemme.
A pre-selection is usually made at the sawmill: the best wood trunks, that means no knots or resonance wood trunks, are destinated to particular applications, and the very bad wood trunks are rejected. Of course the remaining of logs have different diameters, from let's say 14 cm to about 99 cm, so that they are usually separated into seven diameter classes.
In 1991, during the whole month of June, 89 trunks were selected: for each logging zone the volume of the selected timber was in proportion to the yield of different logging zones, for a total volume of 25 m^3. The selected logs belonged to three main diameter classes: small(15-20 cm), medium(26-30 cm) and large (36-40 cm). For each zone, in order to have the required wood volume, a certain number of small, medium and large trunks have been selected. The proportion within small, medium and large diameters was done according to the proportion they may have in the tree, so that the sample can represent better the beams population.
No logs of the best (exellent) quality and worst (rejected) quality have been considered.
Timber was finally sawn into 215 specimens of an unique section:80 x 150 x 4000 mm. The depth of 150 mm was choosen because this is the depth of reference for CEN Standards (no size effect).

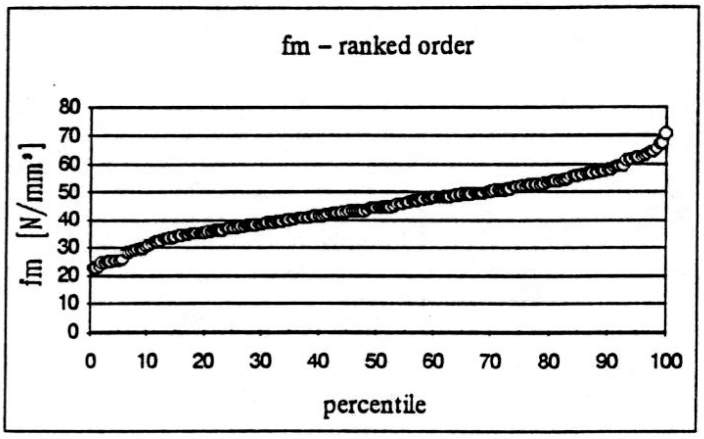
2.2 Testing

Testing of timber pieces have been made according to the procedures given by Standard prEN 408. In particular strength testing was made utilising a four points bending test on a span of 270 cm, that means 18 times the depth of the beam. The strength grade determining defect, within the half length of the piece, was identified by the maximum knot ratio "A" according to DIN 4074/89 . Therefore the weakest point has been randomly positioned in the midspan of the tested beam (randomly means without regard to tension or compression side). The bigger length of the specimen - 400 cm against 270 cm of the test span - allowed this positioning quite easily.
Therefore f_m(MOR) and E_o(MOE) were determined. Also G was determined but utilising three point bending test on a shorter span as mentioned in prEN 408. Density was determined from the weight and volume of the whole specimen. The moisture content for each specimen was determined after rupture according to ISO 3130. Density and MOE values were therefore adjusted to the reference moisture content of 12%.

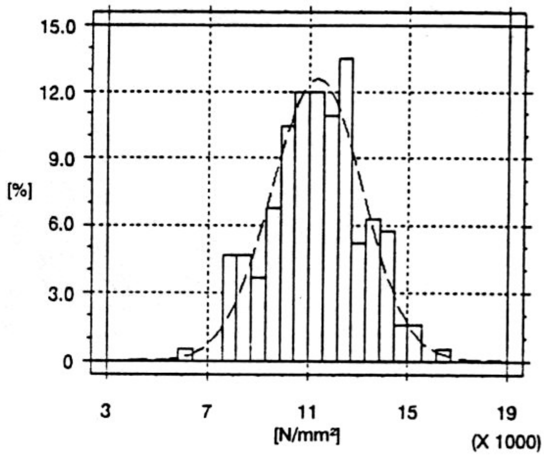
2.2 Test results and their evaluation (whole sample)

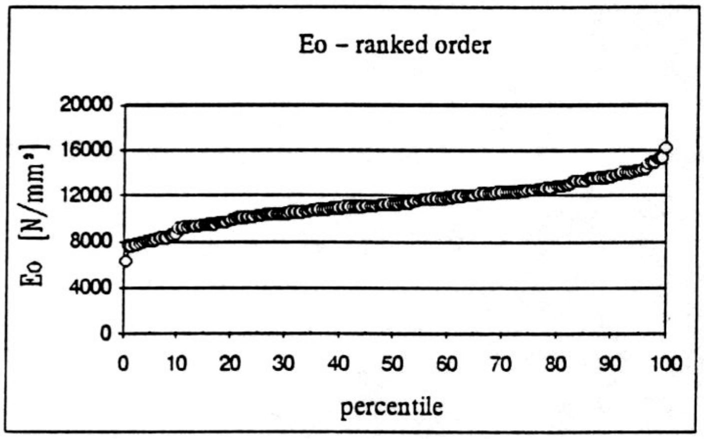
The results of the tests in terms of bending strength, f_m, and modulus of elasticity, E_0, and density, ρ, are given in Fig. 1 as hystograms and ranked order distributions . As required in prEN 384 , the strength characteristic values have been determined as the 5^{th} percentile in a non parametric way (denoted in Fig.1 as $f_{m5\%}$).
Correction coefficient k_s related to the sample size as required in prEN 384 has also been applied, and the final value is denoted in Fig.1 as $f_{m,05}$.
Characteristic MOE ($E_{0,mean}$) and density (ρ_{05}) values have been obtained. For density a normal distribution was considered.
Because density has been measured on the beams and not on the small specimens according to ISO 3131, a reduction coefficient of 1.03, calibrated on preliminary tests, has been adopted instead of 1.05 suggested in prEN 384.
The resulting Strength Class for ungraded material, according to pr EN 338, is therefore C22, as shown in Fig.1 and in the following prospect, where units are N/mm^2 and kg/m^3



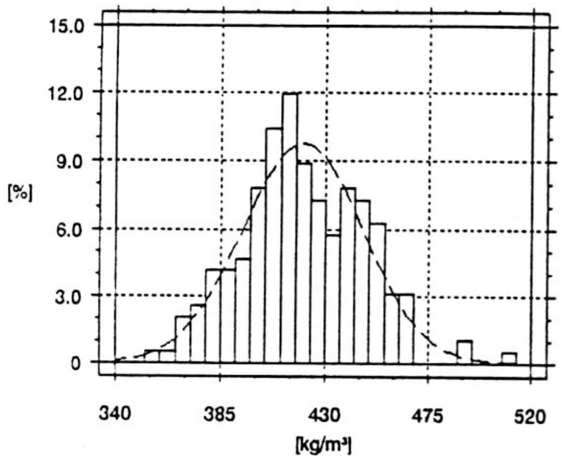


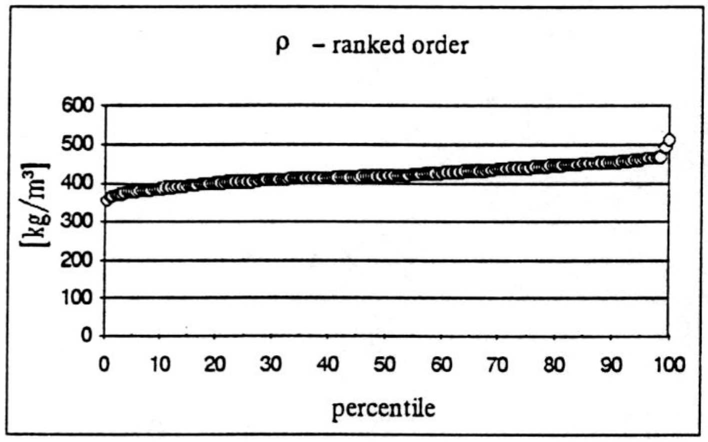
f_m Frequency Histogram – Lognormal Distribution Function





E_0 Frequency Histogram – Normal Distribution Function





ρ Frequency Histogram – Normal Distribution Function

Whole sample	n.	%	$f_{m\,50\%}$ [N/mm²]	$f_{m\,5\%}$ [N/mm²]	k_s	$f_{m,05}$ [N/mm²]	E_{0mean} [N/mm²]	$E_{0,05}$	G	ρ_{mean}	ρ_{05}	EN338 (1993)	Average Class
	192	100.0	44.6	25.4	0.892	22.7	11333	8336	731	420.2	376.9	C22	22

Fig.1 – Test results of the whole sample

respectively for strength/stiffness and density:

	C16	C18	C22	C24	C27	C30
$f_{m.05}$	16	18	22	24	27	30
$E_{0,mean}$	8	9	10	11	12	12
ρ_{05}	310	320	340	350	370	380

It may be useful to recall here the Reader's attention to the fact that all three values - strength, stiffness and density- have to be met for assignment to a Strength Class. Therefore the crucial parameter for assigning a grade into a Strength Class may not always be the value of the characteristic strength but also the characteristic values of MOE and/or density.
The reason why in Fig.1 the sample size is 192 instead of 215 is due to the fact that results related to specimens broken outside the most stressed zone (middle third of the test span) have been disregarded because it may be argued that the weakest point was not correctly positioned; moreover also the test results relative to specimens broken due to shear, and not to bending , were disregarded. In that way the sample size decreased passing from 215 to 192 specimens. In this way results are on the safe side because the failure loads of the specimens broken outside the middle third were homogeneously distributed from smaller to higher strength levels and the failure loads of the specimen broken due to shear were the highest ones (exellent wood quality on the tension side). Therefore obtained results are free of possible contradictory interpretations - also if the Authors opinion is that such values could have been considered in the sample too.

3.Grading

3.1 Visual grading

Visual Grading has been made following DIN 4074/1989 rules. Results are reported in fig 2. It is possible to conclude that grade S13 fits into C30 Strength Class and respectively S10 and S7 into C24 and C16. For this last grade actually the size of the sample is too small to say that in a perfect agreement with the prEN 384 (minimum sample size 40 pieces), therefore the value is given within brackets.
Separation within the grades seems to be good and also $E_{0,mean}$ is well scaled. On the contrary separation of densities is less evident and differences of density within different grades are quite null. Only 0.5% is the percentage of not accepted pieces. The yield for each grade is 29.7 %, 55.7% and 14.1% for S13, S10 and S7 grades respectively.
If we define an "Average strength class" (ASC) weighted on the relevant yield of each grade, in the case of DIN visual grading the average strength class obtained is therefore 24.5 N/mm^2. The ASC may be assumed as measure of the economic yield of the grading system and its value will be recalled in the following for other grading methods.
Of course good economic results obtained by DIN visual grading in laboratory will be someway reduced in the case of practical applications. In fact when knot ratio A is considered along all the length of the timber piece - and not only in the half central part as we made in laboratory - the ASC will decrease (but the result of grading will be more on the safe side).

3.2 Machine grading

visual grade DIN 4074	S13	S10	S7	not accepted	whole sample
size n.	57	107	27	1	192
yield %	29.7	55.7	14.1	0.5	100.0
$f_{m50\%}$ [N/mm²]	53.7	42.3	35.3	–	44.6
$f_{m\,5\%}$ [N/mm²]	39.7	28.2	23.4	–	25.4
K_s	0.805	0.858	(0.75)	–	0.892
$f_{m\,05}$ [N/mm²]	31.9	24.2	17.6	–	22.7
$E_{0\,mean}$ [N/mm²]	12384	11228	9715	–	11333
$E_{0\,05}$ [N/mm²]	10101	8434	7237	–	8336
G [N/mm²]	787	722	658	–	731
ρ_{mean} [kg/m³]	421.5	420.5	416.5	–	420.2
ρ_{05} [kg/m³]	381.7	373.3	381.0	Average Class	376.9
EN 338 (1993) Strength Classes	C30	C24	(C16)	24.5	C22

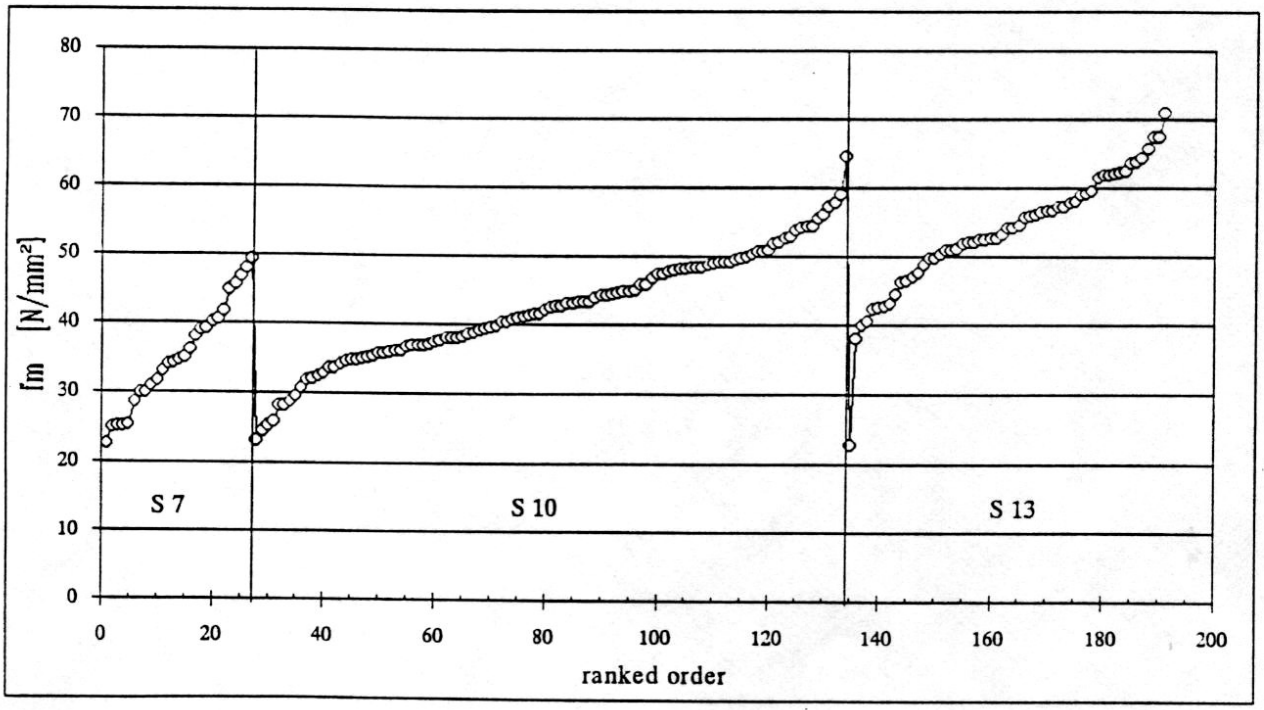


Fig. 2 – Visual grading results according to DIN 4074/1989

Before the rupture test a series of non-destructive tests have been performed. These tests were static (in addition to the four point test on a 270 cm span, a three point loading on 360 cm span was used), and dynamic (longitudinal free vibrations and ultrasonic waves trasmission). Therefore for each specimen, data on the following parameters have been collected:

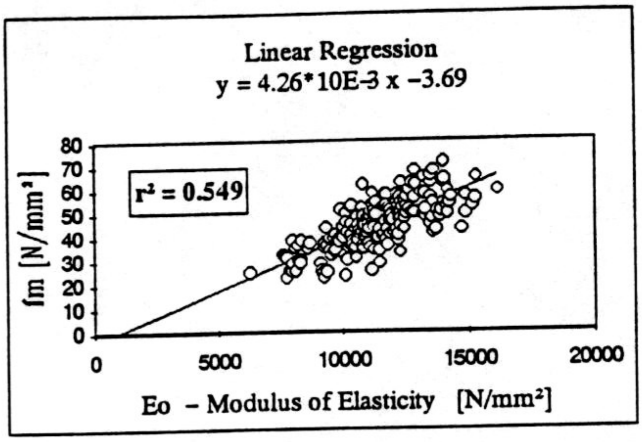
E_0, modulus of elasticity measured according to prEN 408;
E_{0app}, modulus of elasticity one point loading, 360 cm span;
E_{fr}, dynamic modulus of elasticity for longitudinal vibration;
v_{us}, ultrasonic wave speed
E_{us}, dynamic modulus of elasticity evaluated from v_{us} and relevant density

Necessary corrections have been made to take into account differences in moisture in respect to the reference moisture content.
It has to be underlined that all these non destructive parameters are in a certain extent "integral" ones (may be E_0 less than the others), that means that they are "forced" to take into account the "global" behaviour of the beam, and not only the "local" behaviour of the zone that has been supposed to be the weakest one.
The relevant test results are reported in Figures 3,4,5,6 and 7 respectively for E_0, E_{0app}, E_{fr}, E_{us} and v_{us}^2.
As it is possible to see the best correlation is with E_0 and also E_{0app}, that could be easierly used as non-destructive parameter in a strength grade machine in a possible in-line continous control system. In terms of determination coefficient r^2 respect to f_m , we have:

	r^2
E_0	0.549
E_{0app}	0.544
E_{fr}	0.479
E_{us}	0.315
v_{us}^2	0.219

The ultrasonic wave velocity used for the above regression was the tension side one. If the average value of tension and compression side is used, lower values are found (0.18 instead 0.219).
Then separation into grades has been tried. As far as there is something of subjective depending on the choices made (how many grades, optimisation of strengths, MOE, densities and so on, like in a finisseur work) undoubtely this exercise is useful in order to judge the economic yield of possible classifications.
Let us recall the system we used to select different grades. First of all we decided to try to select three grades in order to correspond to the Strength Classes C30-C24-C18. The work has been done step by step selecting at the beginning three values of the non-destructive parameter and checking the resulting Strength Classes trying to optimize the ASC value. It has to be underlined that we did not use the regression line at 5% e.g. obtained with the Curry's system (5th current percentile along constant intervals of the non-destructive parameter). Actually we decided, once separated the sample into groups, to determine the 5th percentile per each group in a non parametric way, utilising the relevant K_s values. In this

machine grade E_0 – Modulus of Elasticity [N/mm²]	I class $E_0 \geq$ 10500	II class $E_0 \geq$ –	III class $E_0 \geq$ 7500	not accepted
size n. yield %	131 68.2	– –	60 31.3	1 0.5
$f_{m\,5\%}$ [N/mm²]	34.3	–	23.2	–
$K_v * K_s$	0.977	–	0.907	–
$f_{m,05}$ [N/mm²]	33.5	–	21.0	–
$E_{0,mean}$ [N/mm²]	12281	–	9348	–
$E_{0,05}$ [N/mm²]	10219	–	7863	–
G_{mean} [N/mm²]	745	–	704	–
ρ_{mean} [kg/m³]	427.1	–	405.3	–
ρ_{05} [kg/m³]	385.2	–	368.9	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.1



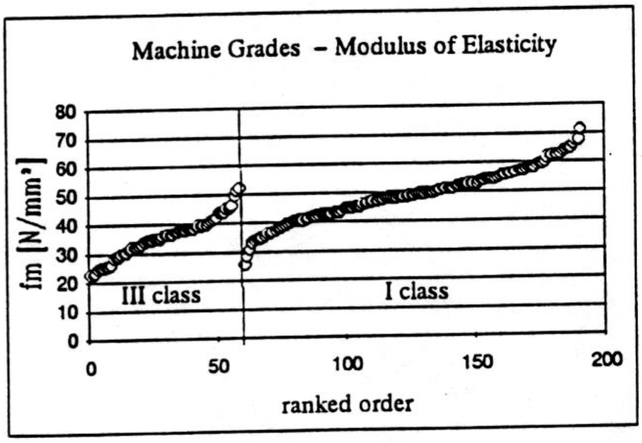
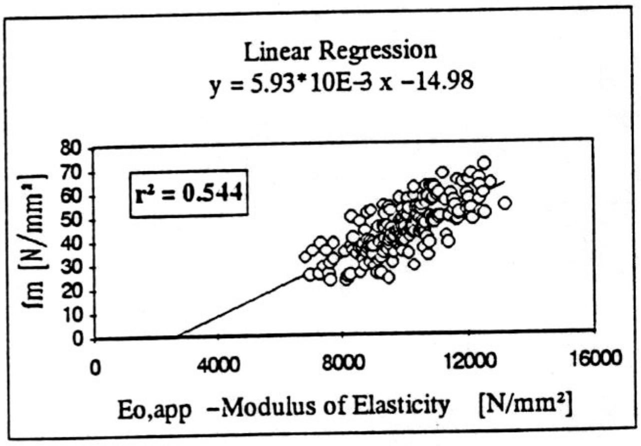


Fig. 3 – Mechanical grading, according to E_0 (prEN 408)

machine grade $E_{0\,app}$ [N/mm²]	I class $E_{0\,app} \geq$ 9300	II class $E_{0\,app} \geq$ –	III class $E_{0\,app} \geq$ 7000	not accepted
size n. yield %	140 72.9	– –	50 26.0	2 1.1
$f_{m\,5\%}$ [N/mm²]	34.0	–	23.6	–
$K_v \cdot K_s$	0.981	–	0.89	–
$f_{m,05}$ [N/mm²]	33.4	–	21.1	–
$E_{0,mean}$ [N/mm²]	12091	–	9385	–
$E_{0,05}$ [N/mm²]	9797	–	7684	–
G_{mean} [N/mm²]	732	–	730	–
ρ_{mean} [kg/m³]	425.2	–	406.8	–
ρ_{05} [kg/m³]	382.1	–	369.5	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.6



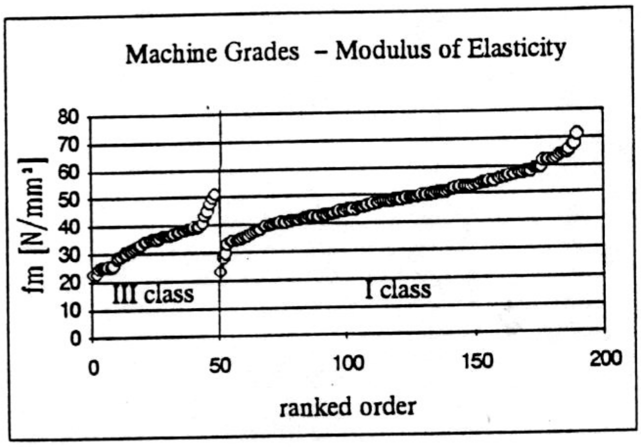
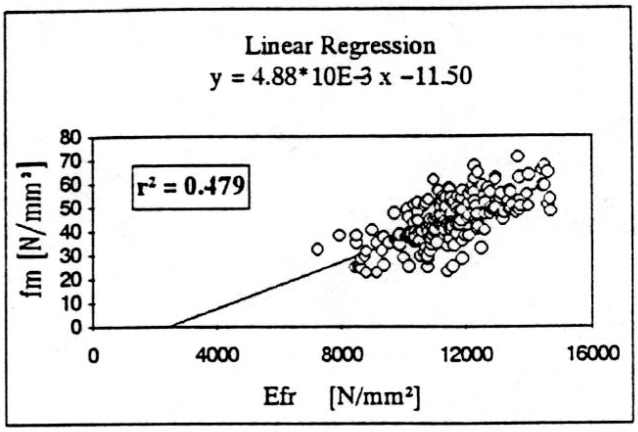


Fig. 4 – Mechanical grading, according to $E_{0,\,app}$ (one point loading, 360 cm span)

machine grade E_{fr} – Frequency MoE [N/mm²]	I class $E_{fr} \geq$ 10800	II class $E_{fr} \geq$ –	III class $E_{fr} \geq$ 7200	not accepted
size n. / yield %	134 / 69.8	– / –	58 / 30.2	– / –
$f_{m\,5\%}$ [N/mm²]	32.7	–	24.4	–
$K_v \cdot K_s$	0.978	–	0.904	–
$f_{m,05}$ [N/mm²]	31.9	–	22.0	–
$E_{0,mean}$ [N/mm²]	12123	–	9506	–
$E_{0,05}$ [N/mm²]	9782	–	7493	–
G_{mean} [N/mm²]	737	–	716	–
ρ_{mean} [kg/m³]	426.5	–	405.7	–
ρ_{05} [kg/m³]	384.4	–	369.4	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.4



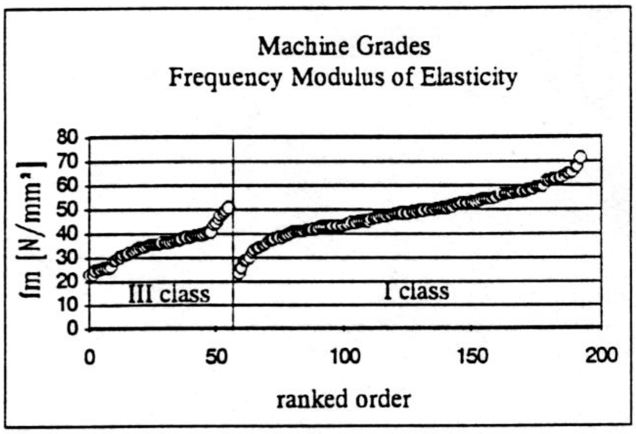
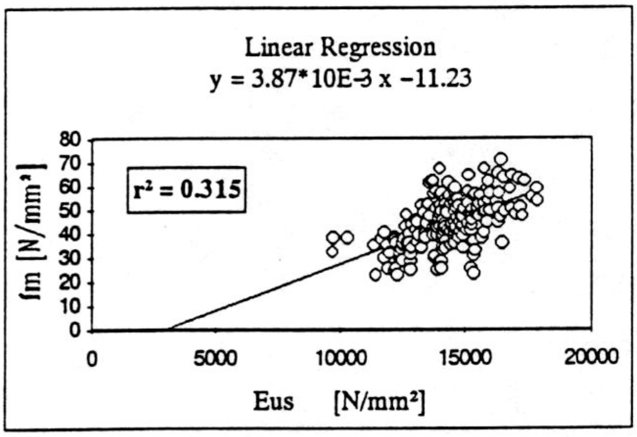


Fig. 5 – Mechanical grading, according to E_{fr} (free vibration in longitudinal direction)

machine grade E_{us} [N/mm²]	I class $E_{us} \geq$ 14000	II class $E_{us} \geq$ –	III class $E_{us} \geq$ 9500	not accepted
size n. / yield %	127 / 66.1	– / –	65 / 33.9	– / –
$f_{m\,5\%}$ [N/mm²]	31.7	–	24.6	–
$K_v * K_s$	0.974	–	0.915	–
$f_{m,05}$ [N/mm²]	30.9	–	22.5	–
$E_{0,mean}$ [N/mm²]	12030	–	9971	–
$E_{0,05}$ [N/mm²]	9394	–	7654	–
G_{mean} [N/mm²]	733	–	726	–
ρ_{mean} [kg/m³]	431.5	–	398.1	–
ρ_{05} [kg/m³]	395.8	–	365.7	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	25.9



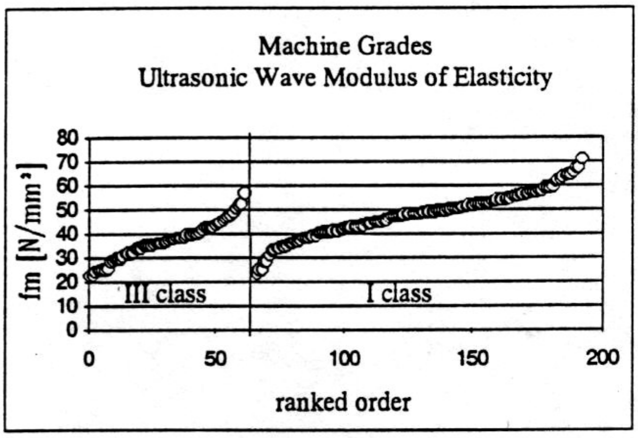
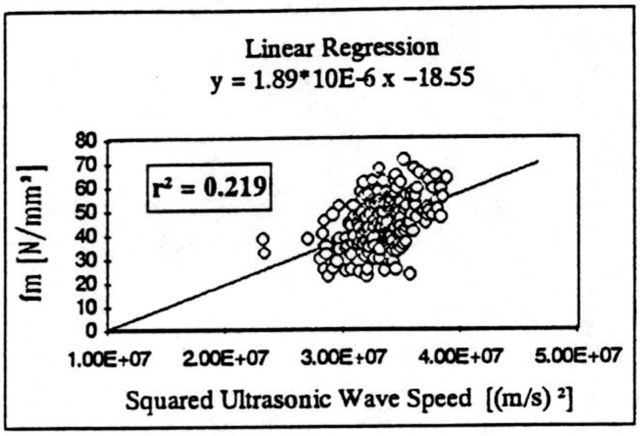


Fig. 6 – Mechanical grading, according to E_{us} (Ultrasonic Wave Modulus of Elasticity)

machine grade v_{us} Ultrasonic Wave Speed [m/s]	I class $v_{us} \geq$ 5900	II class $v_{us} \geq$ 5500	III class $v_{us} \geq$ 4800	not accepted
size n.	53	119	20	–
yield %	27.6	62.0	10.4	–
$f_{m\,5\%}$ [N/mm²]	35.2	25.4	22.6	–
$K_v \cdot K_s$	0.898	0.969	(0.84)	–
$f_{m,05}$ [N/mm²]	31.6	24.6	19.0	–
$E_{0,mean}$ [N/mm²]	12421	11233	9044	–
$E_{0,05}$ [N/mm²]	9907	8571	6852	–
G_{mean} [N/mm²]	737	778	757	–
ρ_{mean} [kg/m³]	425.5	418.7	415.1	–
ρ_{05} [kg/m³]	391.9	372.7	394.7	Average Class
EN 338 (1993) Strength Classes	C30	C24	(C18)	25.0



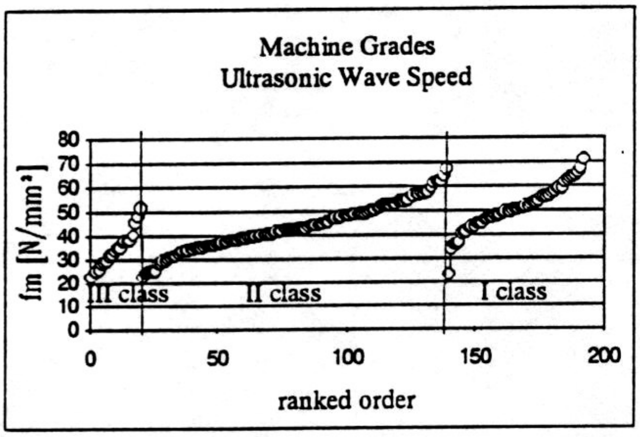
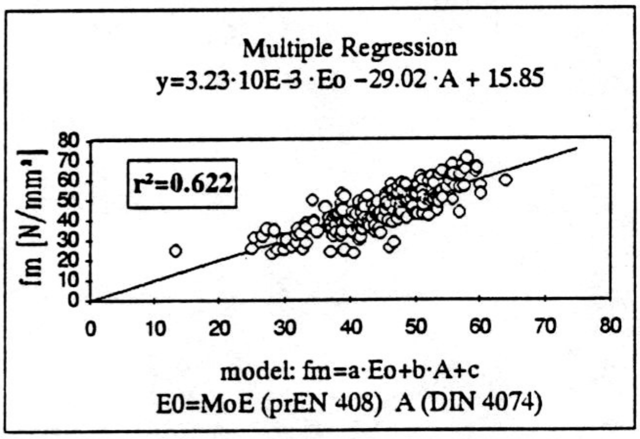


Fig. 7 – Mechanical grading, according to v_{us} (Ultrasonic Wave Speed)

visual – machine grade (mult.regr.) $f_m = aE_0 - bA + c$	I class aE_0+ +bA+c $\geq$ 39.0	II class aE_0+ +bA+c $\geq$ –	III class aE_0+ +bA+c $\geq$ 24.0	not accepted
size n.	144	–	47	1
yield %	75.0	–	24.5	0.5
$f_{m\,5\%}$ [N/mm²]	33.1	–	23.8	–
$K_v \cdot K_s$	0.982	–	0.885	–
$f_{m,05}$ [N/mm²]	32.5	–	21.1	–
$E_{0,mean}$ [N/mm²]	12070	–	9182	–
$E_{0,05}$ [N/mm²]	9812	–	7621	–
G_{mean} [N/mm²]	735	–	723	–
ρ_{mean} [kg/m³]	424.2	–	408.0	–
ρ_{05} [kg/m³]	380.4	–	372.5	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.9



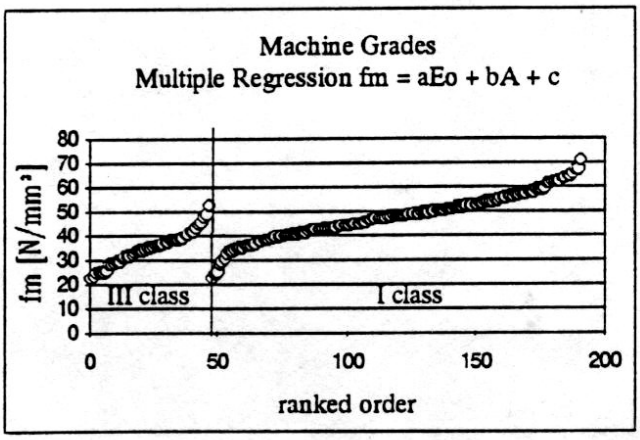


Fig. 8 – Mechanical grading, according to E_0 (prEN 408) – [A] (DIN 4074/1989)

case we used also the k_v coefficient (1.12) as allowed in prEN 384 for taking into account the lower variability of $f_{m,05}$ values for machine grades.
The resulting Average Strength Classes are:

	ASC
E_0	26.1
E_{0app}	26.6
E_{fr}	26.4
E_{us}	25.9
v_{us}^2	25.0

It is probably someway surprising that the differences between good and less good determination coefficient methods -regarding strength- tend to loose some importance if one looks just to the economic yield of the selection. In fact $f_{m,05}$ is not always the crucial parameter, but often also $E_{0,mean}$ and ρ_{05} become decisive for the assignement of a Strength Class so that the ASC cannot increase too much.
Let us give a simple example: with a perfect machine able to "guess" perfectly the strength of a timber piece (that means $r^2=1$, so that each piece of 1st grade is stronger than each piece of the 2nd grade, and so on) the ASC value would be about 35 N/mm^2 if no regard is made to relevant MOE and density values, but ASC is only about 27 N/mm^2 if reference is made also to the two other limiting factors, $E_{0,mean}$ and ρ_{05}, according to prEN 338.

4. Optimal grading

In order to try to optimize the grading we coupled the non- destructive parameters (that give a global evaluation of the beam) with a local parameter (that gives a local evaluation of the beam on the weakest point: in our case the knot ratio A according to DIN 4074 has been chosen). Tentative couplings have been the following with the relevant determination coefficients for f_m:

	r^2
E_0-A	0.622
E_{0app}-A	0.629
E_{fr}-A	0.629
E_{us}-A	0.591
v_{us}^2-A	0.511

In Figures 8,9,10 and 11 the relevant features of these correlations are given. The improvement of the determination coefficient values is noticeable. More it may be surprising the tremendous improvement of r^2 values for ultrasonic based relationships. But, evidently, the coupling with the A factor is a decisive good improvement (r^2 for fm on A, alone, is 0.404). This means that the last relation could be usefully utilized when evaluating structural

visual machine grade (mult.regr.) $f_m = aE_{fr} + bA + c$	I class $aE_{fr}+bA+c$ ≥ 40.0	II class $aE_{fr}+bA+c$ $\geq$ –	III class $aE_{fr}+bA+c$ ≥ 22.0	not accepted
size n.	138	–	53	1
yield %	71.9	–	27.6	0.5
$f_{m\,5\%}$ [N/mm²]	34.0	–	23.0	–
$K_v \cdot K_s$	0.980	–	0.898	–
$f_{m,05}$ [N/mm²]	33.4	–	20.7	–
$E_{0,mean}$ [N/mm²]	12096	–	9442	–
$E_{0,05}$ [N/mm²]	9764	–	7652	–
G_{mean} [N/mm²]	744	–	702	–
ρ_{mean} [kg/m³]	425.8	–	405.7	–
ρ_{05} [kg/m³]	383.3	–	369.4	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.5

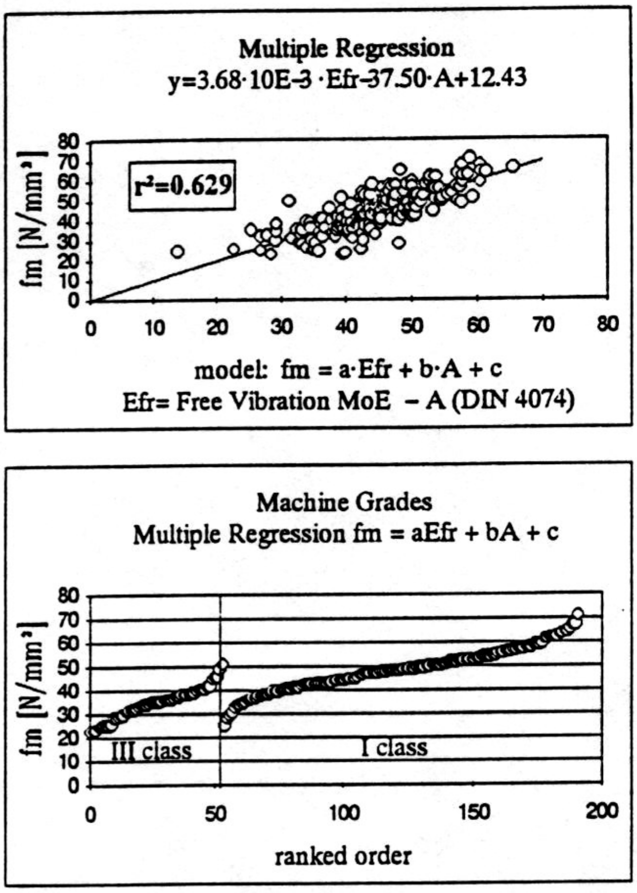


Fig. 9 – Mechanical grading, according to E_{fr} – [A] (DIN 4074/1989)

visual – machine grade (mult.regr.) $f_m = aE_{0\,app}+bA + c$	I class $aE_{0app}+bA+c$ ≥ 39.0	II class $aE_{0app}+bA+c$ $\geq$ –	III class $aE_{0app}+bA+c$ ≥ 22.0	not accepted
size n.	144	–	47	1
yield %	75.0	–	24.5	0.5
$f_{m\,5\%}$ [N/mm²]	33.8	–	23.7	–
$K_v \cdot K_s$	0.982	–	0.885	–
$f_{m,05}$ [N/mm²]	33.2	–	20.9	–
$E_{0,mean}$ [N/mm²]	12011	–	9364	–
$E_{0,05}$ [N/mm²]	9610	–	7582	–
G_{mean} [N/mm²]	740	–	708	–
ρ_{mean} [kg/m³]	424.2	–	408.2	–
ρ_{05} [kg/m³]	380.6	–	371.3	Average Class
EN 338 (1993) Strength Classes	C30	C24	C18	26.9

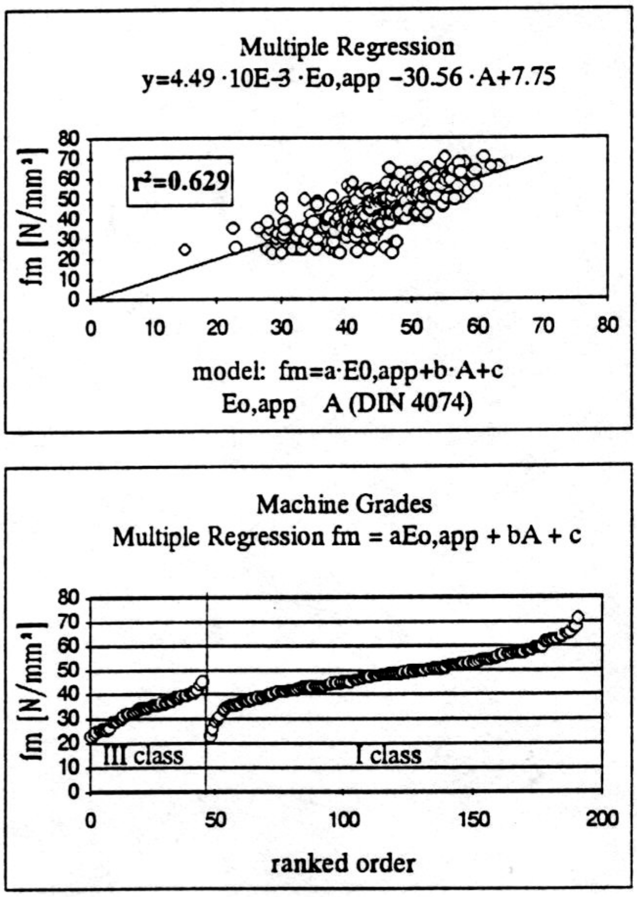
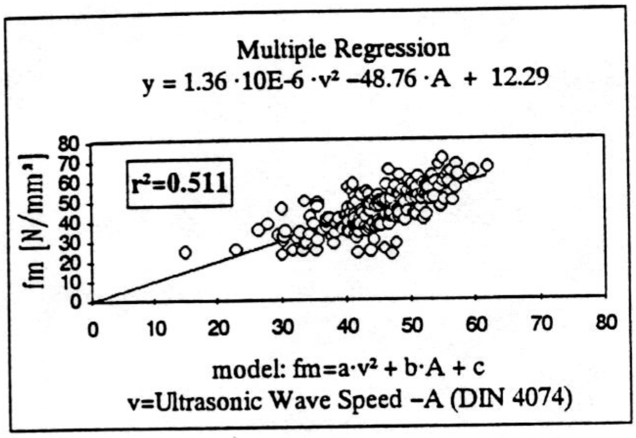


Fig. 10 – Mechanical grading, according to $E_{0\,app}$ – [A] (DIN 4074/1989)

visual – machine grade (mult. regr.) $fm = av_{us}^2 + bA + c$	I class $av_{us}^2 + bA + c$ ≥ 46.0	II class $av_{us}^2 + bA + c$ ≥ 37.0	III class $av_{us}^2 + bA + c$ ≥ 25.0	not accepted
size n.	83	81	26	2
yield %	43.2	42.2	13.5	1.1
$f_{m\,5\%}$ [N/mm²]	39.5	28.9	23.3	–
$K_v \cdot K_s$	0.939	0.936	(0.840)	–
$f_{m,05}$ [N/mm²]	37.1	27.0	19.6	–
$E_{0,mean}$ [N/mm²]	12420	11001	9219	–
$E_{0,05}$ [N/mm²]	10052	8642	7192	–
G_{mean} [N/mm²]	755	715	718	–
ρ_{mean} [kg/m³]	423.6	418.1	416.5	–
ρ_{05} [kg/m³]	383.3	372.7	369.2	Average Class
EN 338 (1993) Strength Classes	C30	C24	(C18)	25.5



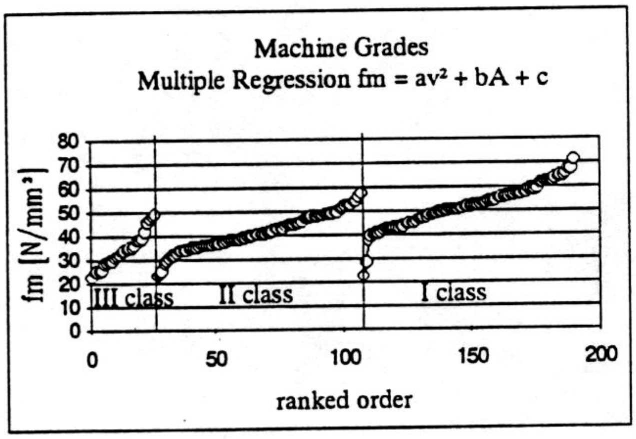


Fig. 11 – Mechanical grading, according to v_{us}^2 – [A] (DIN 4074/1989)

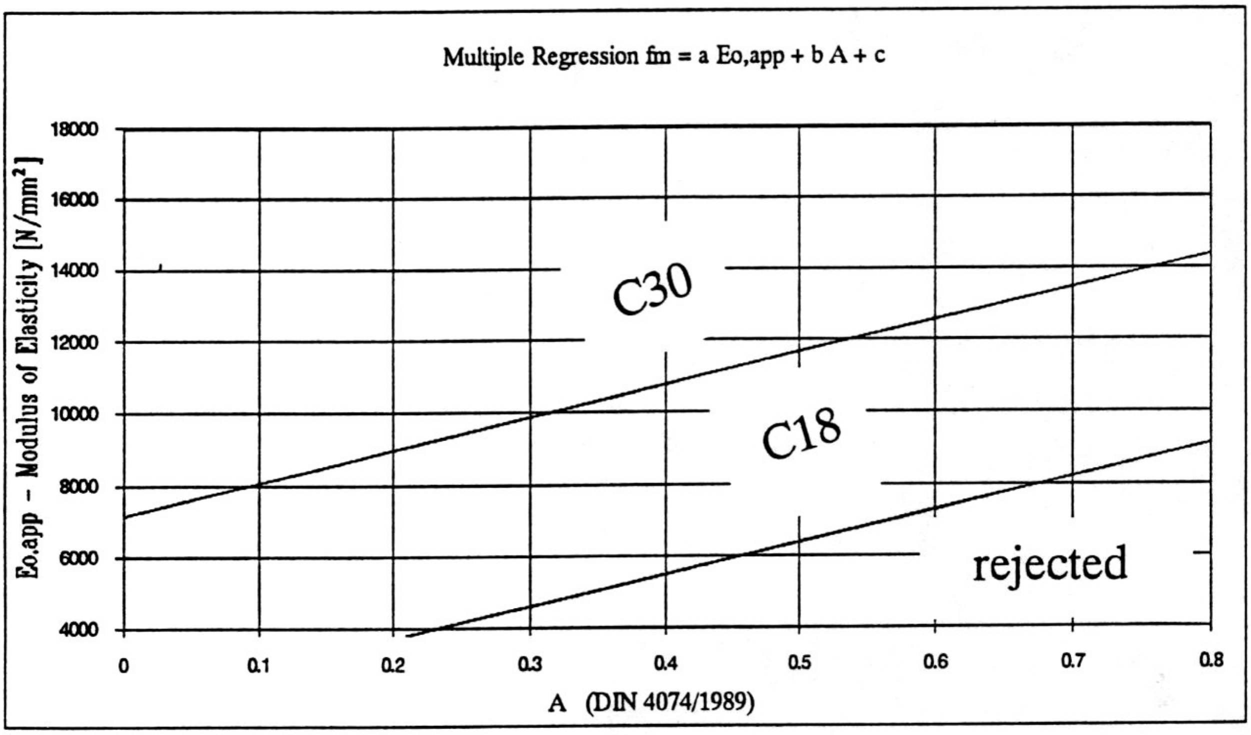


Fig. 12 – Example of a possible grading chart according to $E_{0\,app}$ and [A] (DIN 4074/1989)

timber on site.
And for a possible use at the sawmill with a in-line MOE measuring machine, a possible selecting chart could be something similar to that given in Fig. 12, in case of E_{0app}-A.
Nevertheless the economic improvement in terms of ASC, in respect to one-parameter machine grading is quite null (see the relevant Figures), for the reasons explained above. This means that if one would optimize the Fiemme timber selection on the base of the strength only, he should renounce to fit into the Strength Class System just giving to the Designer the individual strength-stiffness-density profile of the relevant timber grades, that is allowed too by the Eurocode.

5.Conclusions

Spruce timber of Fiemme Valley showed good results for a structural use and, if visually graded according to DIN 4074/89, it fits strength-stiffness-density requirements of the C30-C24-C16 Strength Classes according to Eurocode 5 format.
Non-destructive methods can improve considerably the efficiency of the strength grading. Nevertheless for this timber the rigid profile of Eurocode Strength Classes System does not seem to allow important improvements of the final economic yield when utilising the most sophisticated machine grading methods.

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