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Moisture content and temperature effect on ultrasound timber grading

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Summary. Because wood is a natural material, the variability of its properties is very large. In order to use wood efficiently in building, it has to be stress graded. The ultrasonic stress grading was developped as an improved alternative to visual grading. This non destructive evaluative technique allows reliable higher strength values while working with new products. Corrected models were studied to reference the ultrasonic propagation speed at constant moisture content and temperature. Using a referential ultrasonic wave velocity, stress grading can be carried out on trees or logs before cutting, or on fresh beams. The correlation between conditioned beams and test specimens is very high, especially for the strongest material.

Introduction

Wood as a building material is used in a variety of products, such as roundwood timber or poles, sawn timber, or glued-laminated timber. Because wood is a natural material, a large variability of properties can be found between different species or even in the same tree, resulting in production factors that are very difficult to manage for this engineering product (Panshin, Zeeuw 1980). In order to obtain a product having reliable mechanical properties, wood is controlled during its transformation process, and is later marketed in several mechanical quality classes. Then, each timber construction is designed using a class product concept associated to engineering allowable performances. The design of the project is realized using security concepts (Swiss code SIA 553164, German code DIN 4074, French code NF 52001, etc., ...) or using the new ultimate limit based design (Eurocode 5, Larsen 1991).

The current grading methods are based on visual control. The commonly used criterions are to try to eliminate or to declass beams containing irregularities (knots, resin pockets), important grain angle or even weak density material.

The visual European grading codes were analyzed at the end of a large study of the mechanical properties of Swiss sawn timber based on a sample of 580 beams with commercial sizes (10/14 cm, 10/18 cm, 10/22 cm). The beams were tested in bending according to the specifications of the CIB W18 code, and especially the reference

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Rilem/CIB-3tt (1978). The results showed that the visual techniques are globally uncertain and very different from one country to another, and uneconomic (Kessel, Sandoz 1989; Sandoz 1991).

In order to have a better efficiency in grading, new methods using Non Destructive Evaluation (NDE), were developed. One of the first NDE methods applied to timber (lumber) grading was the stress grading using bending machines, expanded in the 70′ (Snodgrass 1978; Samson 1986). The basic principle of this NDE method is to classify wood in function with the modulus of elasticity (MoE) of the longitudinal axis. The evaluation takes place during the transformation process, using a bending machine. This method has the advantage of being easily applied in an industrial context. Nevertheless, it is adapted to only a few standard cross sections such as lumber, and is not able to perform measurements on standing trees or logs. Nor is it adapted for use at the construction site or on old structures. Because its application area is much more extended, the ultrasonic method has been preferred in our laboratory, as an NDE for timber construction grading. But this method is very sensitive to the moisture content and temperature of wood and required the present extended research.

Grading by ultrasound

The ultrasound grading method developed in Lausanne (Sandoz 1989, 1991) uses the principle of the propagation of ultrasonic waves in the material. The specific equation for wood is (1):

$$V = \sqrt{\frac{C_{LL}}{\varrho}} \tag{1}$$

where

C_{LL} = rigidity constant on the longitudinal axis, L
ϱ = density
V = speed of ultrasound (m/s).

The ultrasound method was applied to a 580 beam sample. The correlation coefficient between speed of ultrasound and MoE, was $r = 0.82$, and between modulus of rupture, MoR, $r = 0.65$. Applying the efficiency of the ultrasound method, as NDE, to the classification of Swiss wood, a new class of high performance timber is being used in building practice in Switzerland. Figure 1 shows the position of the different statistical distributions of MoR corresponding to the Swiss ultrasound classes, including the new class 0. (The weakest beams are in class III.) This result was obtained in laboratory conditions, with a sample conditioned at moisture content, MC = 12%, and temperature, t = 20 °C.

These two physical variables influence strongly the mechanical properties of wood (Kollmann, Krech 1960; Sulzberger 1953). Thus, they influence the stress wave propagation. In order to extend its application to the quality control of trees, logs, fresh sawed beams or in-service timber, the moisture content and temperature effects were studied in order to compute the referential speed of ultrasound (moisture content, MC = 12%, and temperature, t = 20 °C) under any physical conditions.

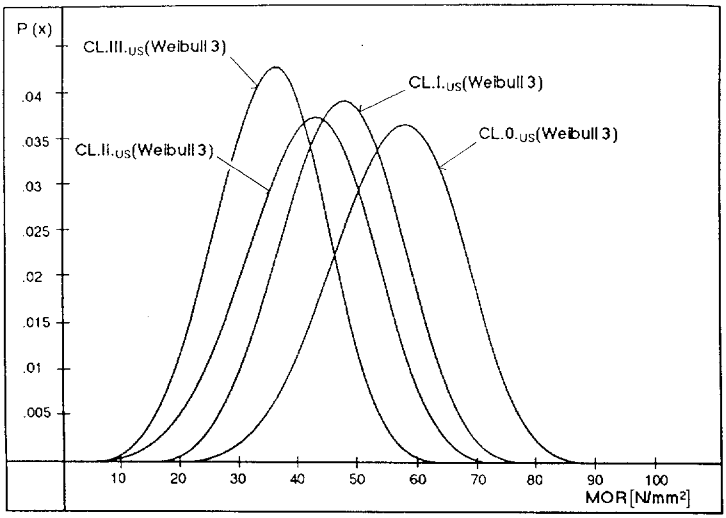

Fig. 1. Probability density functions of the modulus of rupture, MoR, for different ultrasound graded classes, including a new high performance class, class 0. The distributions are three parameter Weibull model based. (Sandoz 1991)

Moisture content effect

Moisture content in wood represent the proportion of water compared with the proportion of anhydric material. From 0% to 25%–30% water is chemically attached to wood with hydrogen liaisons. When all the wood hydroxyl sites are saturated, MC has reached the fiber saturation point, FSP. At the FSP, water is free in the wood cells, and its influence on the wood properties is much less important.

Among the classical techniques used to measure MC, the resistance method integrated in electrical moisture meters was developed during the 40′ (Dunlap, Bell 1951). Often, this method only works in the area below the FSP. In order to know the empirical relationship between the electrical resistance of spruce and fir and their MC, some measurements were performed on small 2/2 cm specimens with a thickness of three millimeters, conditioned at t = 20 °C. The density covered the range from 0.35 to 0.48. For MC > FSP the resistivity measurements were done using a classical ohmmeter. For MC < FSP, a gigaohmmeter was used. MC was controlled by checking the weight of the conditioned sample. Results are shown in Fig. 2. The inverse of MC is expressed in function of the logarithm of the resistivity using a linear model, from MC = 6% to MC = 100%. This empirical equation is allowed to measure MC in spruce and fir. The temperature effect on the electric resistance of wood is corrected using the results of Keylwerth and Noack, 1956. Then, to study the MC effect on ultrasonic stress wave propagation, a sample of spruce and fir was selected in the different quality classes. The speed of ultrasound was measured during the time that MC decreased from 60%, fresh wood, to 15%, dry wood. Specimens were with a length of one meter, with section of 30/30 mm (n = 9), 30/100 mm (n = 7), and (60/100 mm (n = 9). Some results for the 30/30 mm sections are presented in Fig. 3.

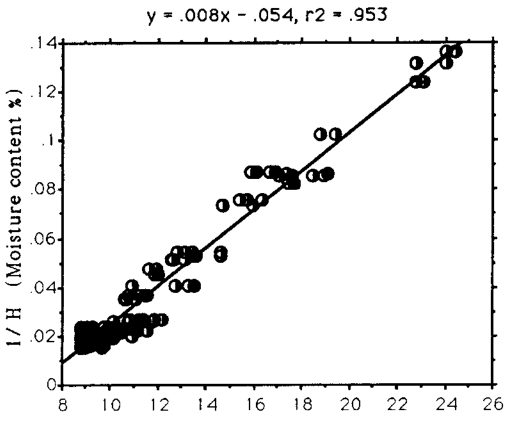

Fig. 2. Relationship between wood logarithmic resistivity and the inverse of moisture content, H_i, for a range of H = 6% to H = 100%

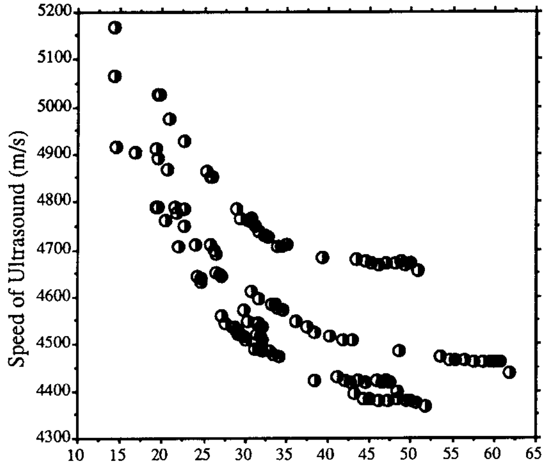

Fig. 3. Influence of moisture content on the ultrasound wave propagation speed in the range of H = 6% to H = 70% for a sample of 30/30 mm cross section

Each of the curves for the complete samples is approximately bilinear with a change in slope at about MC = 32%, which is close to the FSP. This behavior agrees with the well known results of the influence of MC on elastic properties (Kollmann 1984).

Using the test of parallelism for different strait lines ($V = a_i + b_i\ (MC_i - 12)$), modelised for $H < 32\%$ (Seber 1977), the hypothesis H_1: $b_1 = b_2 = \ldots = b_k$ is confirmed (K, number of lines). In this case, the lines for different qualities of wood are essentially parallel, which means that the influence of MC on the ultrasound wave propagation is not affected by the quality of wood. Therefore, for any quality of

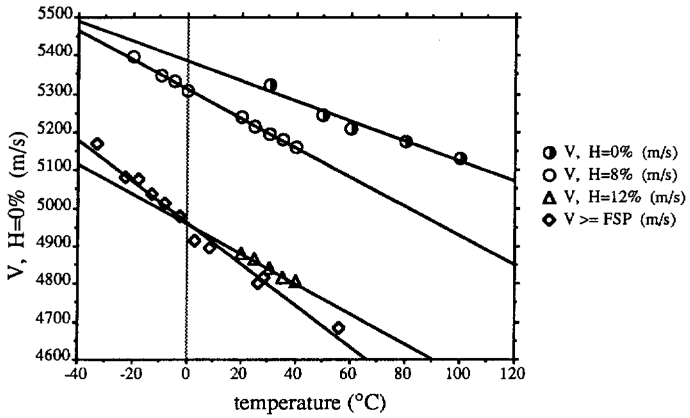

Fig. 4. Influence of temperature on the ultrasound wave propagation speed, V_m, for different moisture contents

wood, the ultrasound wave propagation can be corrected by:

$$(MC \leqq 32\%) \qquad V_r = V_m + 29\,(MC_i - 12) \tag{2}$$

$$(MC > 32\%) \qquad V_r = 580 + V_m + 4\,(MC_i - 32) \tag{3}$$

with

MC_i = moisture content computed with regard to ISO 3130
V_m = speed of ultrasound at MC_i
V_r = referential speed of ultrasound for MC = 12%.

Temperature effect

Temperature effect on ultrasonic stress wave propagation has been studied using a sample with a specimen length of one meter, conditioned at several MC levels, and with the following undersample:

MC = 0%	50/60 mm	n = 12
MC = 8%	50/60 mm	n = 12
MC = 12%	60/60 mm	n = 12
MC ≥ PSF	30/30 mm	n = 12.

MC was controlled checking weight of the packed specimen. Temperature changed from 60 °C to −20 °C. Figure 4 shows that the speed of ultrasound, V, decreases when temperature is increasing. The phenomena is perfectly linear, even around the temperature of 0 °C. It appears that the slope of the lines decreases as MC increases. In Fig. 5, the slopes of the lines of Fig. 4 are plotted against MC and result in a linear cross effect of MC below the FSP. Deduced from this result, the measured speed, V_m, can be corrected by the temperature using Eqs. (4) and (5):

$$V_r = V_m + k_1\,(t - 20) \tag{4}$$

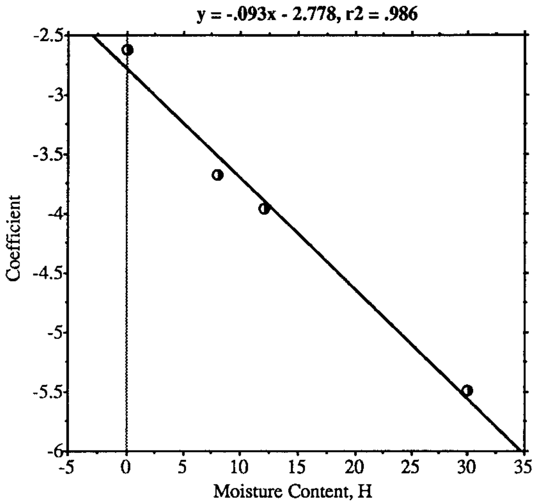

Fig. 5. Effect of moisture content on the slope of the temperature versus propagation speed relationship observed in Fig. 4

Table 1. Class results and statistical mechanical values obtained with the ultrasound grading applied to logs, before to be sawed

	V_r	n	MoE	MoR		
				Mean	Standard deviation	5% fractile
	[m/s]		[N/mm^2]	[N/mm^2]	[N/mm^2]	[N/mm^2]
Class 0	≥ 5650	16	15156	61.9	9.4	46.4
Class I	$5500 \leq V_r < 5650$	8	14772	60.55	12.6	39.9
Class II	$5350 \leq V_r < 5500$	4	12652	55.4	15.9	29.1
Class III	$4800 \leq V_r < 5350$	17	11090	42.1	10.7	24.4
Out of class	< 4800	4	10312	43.3	12.2	23.2

and

$$k_1 = -0.093\,H - 2.78 \tag{5}$$

Timber grading

In order to control the efficiency of the ultrasonic grading for diverse applications (especially on logs before cutting, or on fresh beams), a grading was done on 40 spruce

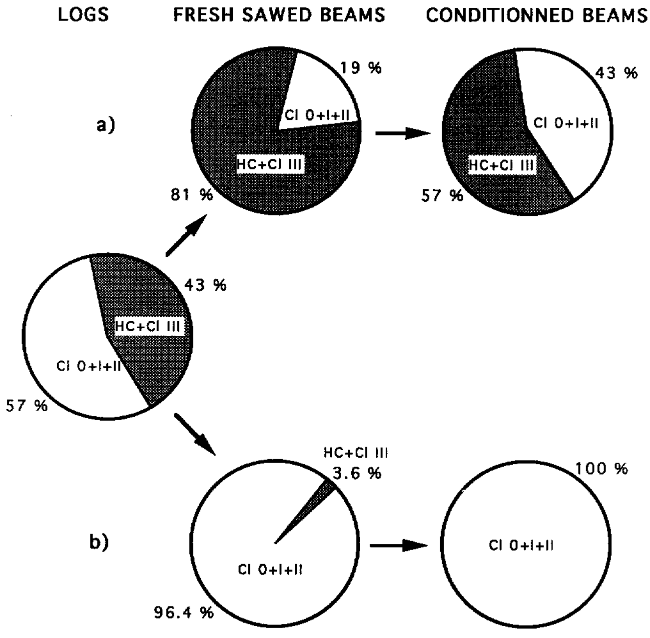

Fig. 6 a and b. Ultrasound grading applied to logs. Evolution of the grading at the different levels of transformation from log to conditioned beams. a) weakest beams; b) strongest beams

and fir logs using Sylvatest®, the instrument developed for testing the mechanical quality of timber which integrated the results of the preceding sections. One beam of section 8/16 cm was cut from each log, graded one more time when MC > FSP, conditioned, and then graded for the last time, when MC = 12%, before being tested in bending, as defined before.

Table 1 gives the log grading results in term of classes and mechanical values. The efficiency of the ultrasound grading is well confirmed with regard to the MoE and 5% fractile of MoR, despite the low statistical dimension of the sample. Grouping together the classes HC and III, the weakest beams, and the classes 0, I, II, the strongest beams, Fig. 6 shows the progression in grading from log to conditioned beam. It seems that for the weakest beams, some of them could be upgraded as result of the measurement taken. This result is compatible with the fact that Sylvatest® accommodates for a MC less of 50% only. Up this value, MC is neglected because the low accuracy of the resistivity measurements. For the strongest beams, the log grading conformed completely with grading on conditioned beams. Thus, the ultrasound method is very reliable even when applied to logs before sawing.

Conclusions

Because of the variability of its mechanical properties, wood as an engineering material has to be stress graded. The graded classes will link allowable stresses with regards to economic and reliability considerations. The actual visual based grading methods are complex, uncertain, and unreliable, justifying the need for NDE methods like the ultrasound technique. In order to take into account the moisture content and temperature effect on the ultrasonic stress wave propagation, empirical corrected models were calibrated. Moisture content can be measured according to resistivity of wood and corrected using a bilinear model with a change of the slope at $MC = 32\%$ (for spruce and fir). The MC effect for $MC < FSP$ is approximately eight times the MC effect when $MC > FSP$. The corrected equation for the temperature effect is linear. It changes in function with MC. Using these corrected models, ultrasonic grading can be applied on logs before sawing as well as on fresh beams. Some tests performed with Sylvatest®, the ultrasonic instrument for testing the mechanical quality of timber, have shown the perfect reliability of log grading compared with the grading of conditioned beams, especially for the strongest material.

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