Structural Analysis of Historical Constructions, New Delhi 2006
P.B. Lourenço, P. Roca, C. Modena, S. Agrawal (Eds.)

Acousto-Ultrasonic Non-Destructive Evaluation of Historical Wooden Structures

Jean-Luc Sandoz
CBS – Concepts Bois Structure, Les Ecorces, France

Yann Benoit
CBT – Concept Bois Technologie, Saint-Sulpice, Switzerland

ABSTRACT: The evaluation of timber mechanical properties is multi-varied due to several factors affecting the material such as the growing conditions, the knots, the density, the annual rings, the slope of grain etc.

The acousto-ultrasonic method is a very effective technology to evaluate the residual mechanical performances of wooden elements, for roofing, decking or walls (wooden columns).

The Sylvatest-Duo device manages this technology and allows a direct monitoring for the safety and the service of the inspected historical constructions.

The use of the acoustic phenomenon is very helpful for the detection of local singularities like the evaluation of risks due to a crack for example.

This paper relates the development of the Acousto-Ultrasonic technology especially concerning the longitudinal measurements for the evaluation of the MOE (Modulus of Elasticity) and the MOR (Modulus of Rupture) and its applications for a wooden structure expertise.

With the results of the Sylvatest Duo device, the priorities of renovation can be clearly highlighted.

1 INTRODUCTION

The use of wood as a structural material dates from the early first constructions humans could have done.

This available resource was used for the primary constructions as individual buildings, but was also rapidly associated to the stone for major buildings such as camps, temples, palaces, or castles.

Years after years, centuries after centuries, wood was then commonly present as a structural frame and more especially for decking and roofing.

If fire (Rom under Nero in 64 after JC, London in 1666 after JC) and biological attacks are the main sources of wood degradation, many secular constructions show excellent examples of wood uses.

Today, the security of visited buildings and the renovation of the historical heritage ask for a precise knowledge of the existing frames performances. Architects and engineers must evaluate the quality of a structure in order to be able to plan its replacement, its renovation or, in the best case, its conservation.

As a biological material and due to many environmental effects, wood, even from a same species, has a wide range of mechanical properties (kollmann and Cote 1984). These properties are the basis for any design using the material and are defined in the standards.

For example, in Europe, the EN338 standard relates the mechanical properties for sawn timber. Table 1 presents the different classes of mechanical properties for softwood established in the EN338.

Table 1 : Mechanical values for timber design, according to the European standards EN 388.

Characteristics	Symbol	C 14	C 16	C 18	C 22	C 24	C 27	C 30	C 35	C 40
		Strength classes								
Bending [N/mm^2]	$f_{m,k}$	14	16	18	22	24	27	30	35	40
Tension ‖ [N/mm^2]	$f_{t,0,k}$	8	10	11	13	14	16	18	21	24
Tension ⊥ [N/mm^2]	$f_{t,90,k}$	0,3	0,3	0,3	0,3	0,4	0,4	0,4	0,4	0,4
Compression ‖ [N/mm^2]	$f_{c,0,k}$	16	17	18	20	21	22	23	25	26
Compression ⊥ [N/mm^2]	$f_{c,90,k}$	4,3	4,6	4,8	5,1	5,3	5,6	5,7	6,0	6,3
Shear [N/mm^2]	$f_{v,k}$	1,7	1,8	2,0	2,4	2,5	2,8	3,0	3,3	3,8
Elasticity modulus [kN/mm^2]										
– parallel average	$E_{0,mean}$	7	8	9	10	11	12	12	13	14
– parallel $f_{5\%}$	$E_{0,0.5}$	4,7	5,4	6,0	6,7	7,4	8,0	8,0	8,7	9,4
– perpendicular average	$E_{90,mean}$	0,23	0,27	0,30	0,33	0,37	0,40	0,40	0,43	0,47
Shear modulus average	G_{mean}	0,44	0,50	0,56	0,63	0,69	0,75	0,75	0,81	0,88
[kN/mm^2]Density minima	ρ_k	290	310	320	340	350	370	380	400	420
[kg/m^3]Density average [kg/m^3]	ρ_{mean}	350	370	380	410	420	450	460	480	500

From the last decade, new technologies have been developed in order to evaluate the mechanical properties of wood by using non-destructive testing. Previously, only visual grading was recognized, penalizing the material by the method's low accuracy.

In the next chapters, the development of an effective non-destructive technology, Sylvatest Duo, using acousto-ultrasonic for wood grading is described.

2 NON-DESTRUCTIVE TECHNOLOGY USING ACOUSTO-ULTRASONIC

2.1 The ultrasonic measurement

From 1985, the ultrasonic method for the measurement of the mechanical performances of timber – the modulus of elasticity: $MoE_{\|}$ and the bending resistance: σ_b – has been validated for the wood as a structural material.

At the end of the 80's, a technology transfer has been realised with the Sylvatest device (Sandoz 1989) through the results of a thesis work (Sandoz 1990). This device was based on the measurement of the speed of propagation of a low frequency wave transmitted in the longitudinal axis of the wood (Fig. 1) as shown on the equation (1):

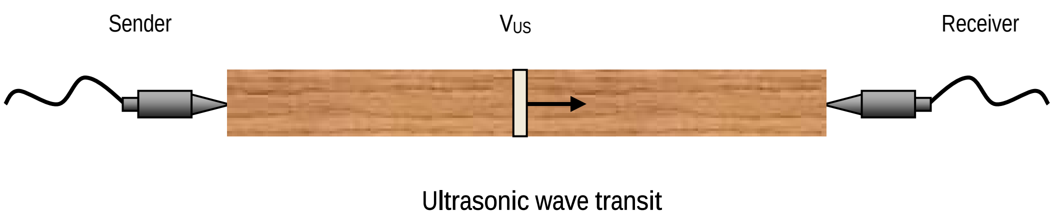

Figure 1 : Longitudinal ultrasonic measurement in a wood piece.

$$V_L = \sqrt{\frac{C_{LL}}{\rho}} = \sqrt{\frac{MoE_{//}}{\rho.1.82}} \tag{1}$$

For a species such as spruce, a calibrated model giving the $MoE_{\|}$ and the bending strength σ_b can be written as follow (equations 2 and 3):

$$MOE_{//} = \alpha_1 V_L + \beta_1 \tag{2}$$

$$\sigma_b = \alpha_2 V_L + \beta_2 \tag{3}$$

Where:
V_L: the waves' velocity in the longitudinal axis [m/s];
$MoE_{//}$: the modulus of elasticity parallel to the grain [N/mm^2];
ρ: the density of the material [kg/m^3];
σ_b: the bending modulus of rupture [N/mm^2];
α, and β: calibration parameters.

On the basis of these models obtained by ultrasonic measurements, Switzerland could have validated the 0 class ($MoE_{||}$ = 14 000 N/mm^2 and σ_b = 17 N/mm^2), and then the 0^+ class ($MoE_{||}$ = 15 000 N/mm^2 and σ_b = 20 N/mm^2), 10 years before the arrival of the Swisscodes based on the European grading of the EN 388 standards (Table 1).

2.2 The Acousto-Ultrasonic measurement

In 1998, IBOIS, the laboratory for timber construction of the Swiss Federal Institute of Technology in Lausanne, has developed and improved the ultrasonic technology for wood.

The new generation of device, Sylvatest Duo, deals with the analysis of the acousto ultrasonic response of the wood (Sandoz 2000) (Fig. 2).

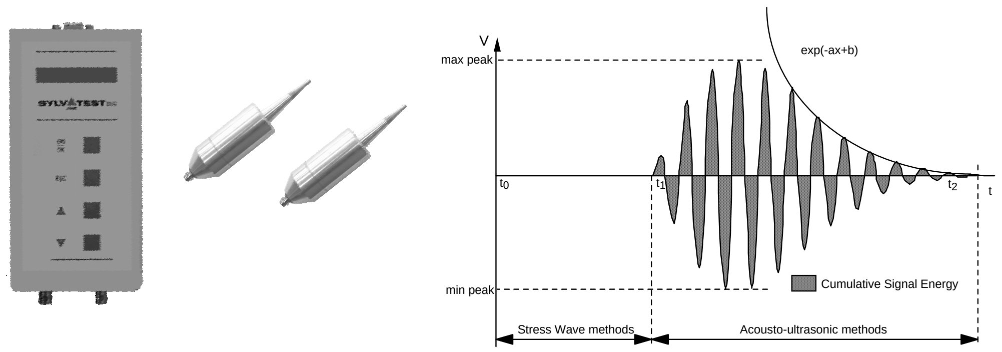

Figure 2 : Sylvatest-Duo and its transducers (left) and analysis of the acousto-ultrasonic signal with the measurements of the speed and of the maximal peak of energy of the transmitted waves (right).

The system always measures the speed of the transmitted low frequency wave (20 kHz), and measures then the maximal peak of energy of these waves thanks to the equipment presented by the Fig. 2.

The speed of propagation is still correlated to the modulus of elasticity ($MoE_{||}$), but the energy is correlated to the local singularities (knots, grain direction, degradation area…).

In fact, the energy damping of the waves is directly dependant of local singularities. The maximal value of the peak of energy represents thus a measurement of the acoustic response of the wood which translates faithfully the damping function.

This new generation of device, able to measure and manage the two acousto-ultrasonic variables, allows working in the wood natural axis: the longitudinal, radial and the transversal ones.

2.2.1 The longitudinal mode

Applied to the longitudinal mode, the two measured acousto-ultrasonic variables, the speed V_L and the peak P_{max}, allow the evaluation of the two basic properties of a structural wooden element (equations 4 and 5):

– The modulus of elasticity $MoE_{||}$:

$$MoE_{//} = \alpha_1 V_L + \beta_1 P_{\max} + k_1 \quad (4)$$

– The critical bending strength σ_b:
–

$$\sigma_b = \alpha_2 V_L + \beta_2 P_{\max} + k_2 \quad (5)$$

With the wood for structures, the equation based on the simplified Hooke's law, on the longitudinal axis (equation 6) is very poor, because of the stochastic influence of the local singularities on a wood sample at the macroscopic scale.

$$\varepsilon_L = \frac{\sigma_L}{MoE_L} \tag{6}$$

Where:
V_L: the waves' velocity in the longitudinal axis [m/s];
ε_L: deformation on the longitudinal axis [mm];
σ_L: longitudinal strength [N/mm^2];
E_L: longitudinal modulus of elasticity [N/mm^2];
P_{max}: the maximal peak of energy of the transmitted wave [mV];
α, β, k: calibration parameters.

The reliability obtained thanks to the equation 5 is much higher than the one obtained previously (equation 3) because the influence of the modulus of elasticity $MoE_{||}$ (equation 4) and the singularities are integrated, via the measurement of the maximal peak of energy: P_{max}.
For each species, a specific model is obtained after four points bending tests. The coefficient of determination r^2 relates the reliability of the evaluation with the failure tests results. Figs. 3 and 4 present the reliability for different species: Oak, Spruce/Fir (Sandoz 2000) and the exotic species Gmelina (Karlinasari and Nugroho 2006).

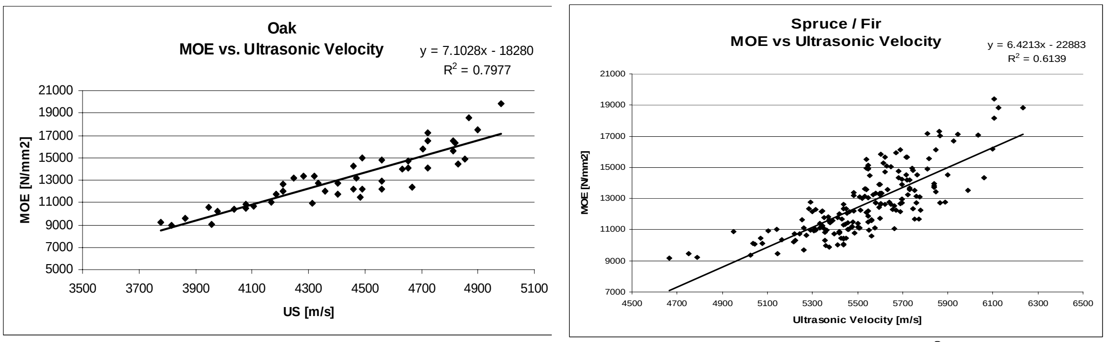

Figure 3 : Tests results with Sylvatest Duo non-destructive evaluation for oak (left, r^2=0.7977) and spruce/fir (right, r^2=0.6139).

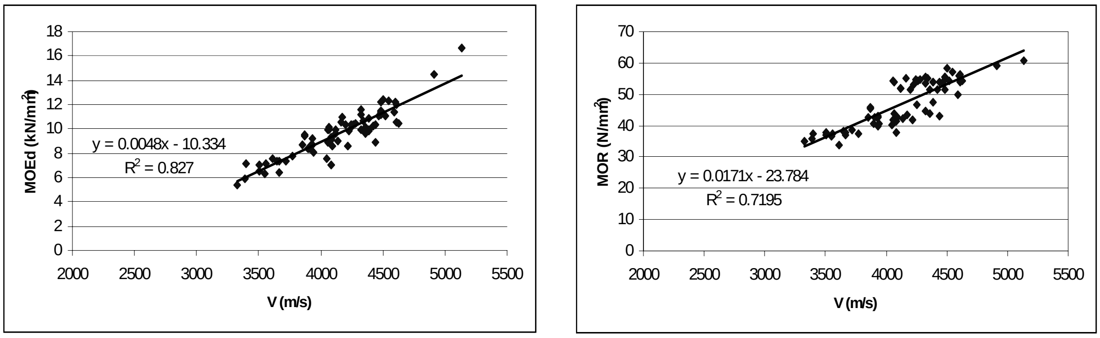

Figure 4 : Tests results with Sylvatest Duo non-destructive evaluation for Gmelina Arborea from Malaysia (left, MOE, r^2=0.827; right, MOR, r^2=0.7195).

The Fig. 5 shows an industrial application of a mechanical grading of wooden elements developed for a glue-laminated timber company, using longitudinal acousto-ultrasonic measurements.

In this case, an electronic processor, the Duomatic, enables the machine, Sylvamatic, to work on line in the production process. In order to increase the cadence, (about 200 m/min), this machine can work with multiple heads (2, 4 or 8 pairs of transducers).

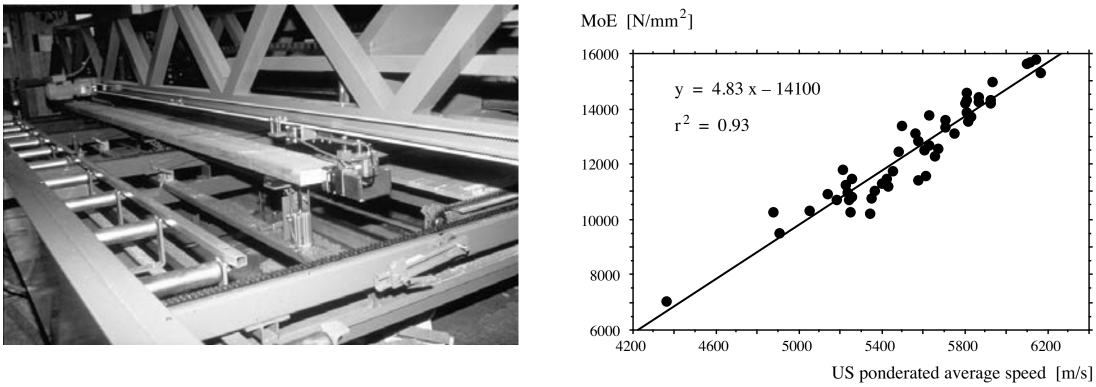

Figure 5 : Industrial application of mechanical grading by acousto-ultrasonic method (left) and its reliability for gluelam beams (right).

For each application, the measurements are exploited by the software Sylvius which transfers directly the exploitable results to the operator or to management system for an appropriate products flow.

2.2.2 The transversal mode

The transversal mode is mainly used for the local singularities detection. This mode is based on comparative measurements: a decayed area is compared to a supposed sane area in order to evaluate an eventual material's weakness.

In many cases, the uncertain areas are known: transversal gluing plane for the glue laminated timber beams, assembling zones for traditional carpentries or base of wooden columns for example as described by the Fig. 6.

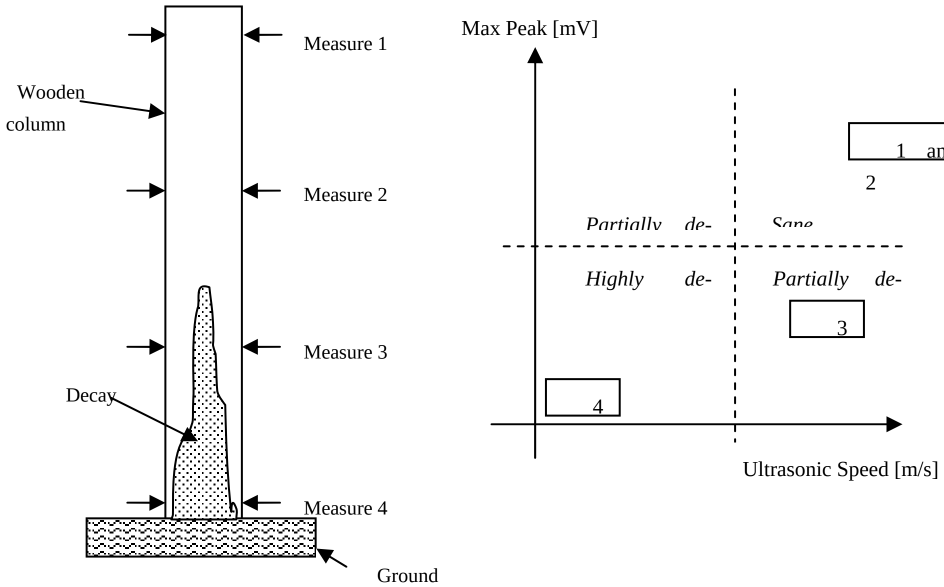

Figure 6 : Example of a wooden column analysis: comparative measurements all along the column to detect internal defaults.

About the results of the comparative measurements, the ultrasonic parameter (the speed of the transmitted waves) is less critical than the acoustic one. Indeed, for the small singularities as shown in this example, the energy damping can be clearly observed, what is not the case with the speed of the ultrasounds.

The main difficulty with this application is the coupling mode between the transducers and the wood. Indeed, a constant force must be applied in order to compare the results, because the acoustic parameter is very influenced by this characteristic.

With the results obtained today, the nature of the singularity can not be given by the device. But for each application, the kind of singularity can be estimated according to the source of the eventual problem. For example, a singularity found in a finger joint zone would signify a lack of gluing in this area and for a wooden column, the principal default of the base is a biological decay.

3 APPLICATION TO HISTORICAL MONUMENTS EXPERTISES

Thanks to the Sylvatest-Duo technology, the CBS-CBT experts could have managed some important expertises around the world on some major wooden historical constructions. Some examples are now presented in this section.

3.1 The Forbidden City, Beijing, China

With the collaboration of the Tsinghua University of Beijing, CBS-CBT had to evaluate the residual strength of wooden columns of the major temple of the Forbidden City to detect whether a renovation should be applied or not (Fig. 7).

The wooden columns are composed by four quarter of cylinder. So each quarter of cylinder should have been measured separately as presented by the Fig. 8. Then, a static calculation could determine the global residual strength of each wooden column of the historical temple.

Figure 7 : Expertise of the Forbidden City, Beijing, China. Analyse of the quality of the wooden columns thanks the non-destructive technology Sylvatest-Duo.

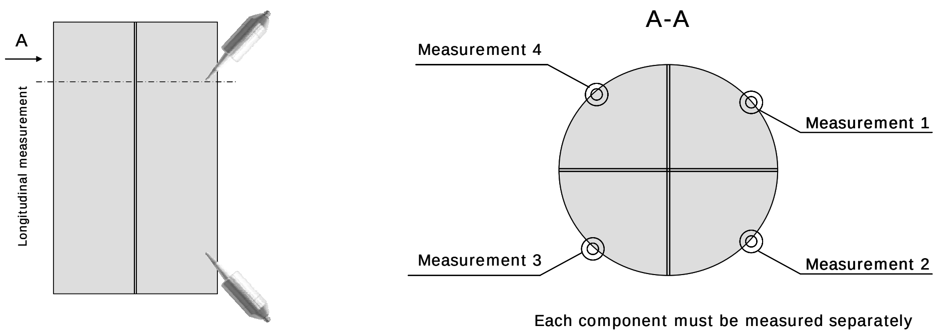

Figure 8 : Wooden columns of the Forbidden City composed by four quarter of cylinder. Each piece must be separately measured by the Sylvatest-Duo in the longitudinal axis for the global resistance evaluation.

3.2 Valere's Castle, Sion, Switzerland.

Le Château de Valère (Valere's castel), built in the XIIIth century in Sion, Switzerland, has been inspected in 2001 in order to define the renovation works to be planed for the installation of a library and a museum for the visitors (Fig. 9).

The aim of this expertise was the wooden beams inspection to obtain the global quality of each floor. So, each wooden beam was individually measured by the Sylvatest-Duo technology with the longitudinal measurement in order to evaluate the wood residual strength.

With the results, a monitoring (Fig. 10) could have been drawn to present the quality of each wooden beam with a special colour depending of the resistance class defined by the standards (Table 1).

Thanks to this monitoring, architects and engineers had exactly the status of the mechanical properties of each slab and could then manage their works with optimized costs.

Figure 9 : Valere's Castle, Sion, Switzerland, built during the XIIIth century. Non-destructive evaluation of the wood residual strength by using Sylvatest-Duo.

Figure 10 : Monitoring displaying the Sylvatest-Duo results with a specific colour for each wooden beam according to the standards resistance classes.

3.3 Frequently asked questions concerning the use of the Acousto-Ultrasonic method for historical building expertises

If the acousto-ultrasonic method covers a wide range of applications, some questions still exist concerning the historical monument expertises.

The main concern deals with the wood-transducers coupling. This point is very important because a bad manipulation can change the results. It is for this reason why wood is drilled in order to install the transducers properly. Small holes of 1cm depth and 1 cm diameter are then operated in the wood.

The second concern is about the species. If Sylvatest Duo has many models for many species, some of them are still inexistent in the database. For this case, the studied species is approached by the closest know species. This can be done thanks to the knowledge of the wood molecular structure and the experiments done years after years by the worldwide universities sharing their data. Statistics results can also help to define the most appropriate model.

The length of measurements is not a concern. The power of the equipment allows measurement up to 20 meters, largely sufficient in the historical monument expertises.

The measurements must be made in a quite environment. Indeed, the measured value is a time of flight of ultrasonic waves. Shocks and high noises can affect the measurements.

At least, as for any device, the expert must know what he is expecting in his measurement. A critical eye and a good knowledge of wood avoid many complications.

4 CONCLUSIONS

As a conclusion, it can be noticed that the acousto-ultrasonic technology – Sylvatest Duo – is an appropriate tool for the expertises of historical wooden structures.

The residual mechanical performances can be evaluated and are directly related to the standards values. A monitoring of the structure can be then drawn according to the expertise results (Fig. 10).

Thanks to these results, architects and engineers can focus their priorities of actions, saving thus money, and sometimes, the structure itself.

If the knowledge of the material is indispensable for an optimal use of the device, based on this non-destructive technology, the expert has a real help in his surveying works.

REFERENCES

Kollmann, F. P.; Cote, W. A., 1984: *Principles of Wood Science and Technology*, Ed. Springer Verlag

European Standards for Timber Construction EN338. Mechanical properties for sawn wood used as a structural material

Sandoz, J.-L., 1989: *Grading of construction timber by ultrasound*, Wood Science and Technology 23:95-108

Sandoz, J.-L., 1990: Grading and reliability of construction timber, validation of the ultrasound method, thesis n°851, EPFL, IBOIS, Lausanne, Switzerland

Sandoz, J.-L.; Benoit, Y.; Demay, L., 2000: Wood testing using acousto-ultrasonic, *World Conference on Timber Engeneering*, Whistler, Canada.

Karlinasari, L.; Nugroho, N., 2006: Non Destructive Ultrasonic Method Testing on Bending Strength Properties of Gmelina Wood (*Gmelina arborea Roxb*.), Department of Forest Products, Faculty of Forestry, Bogor Agricultural University, Indonesia