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ASSESSMENT OF TIMBER STRUCTURES IN SERVICE, BY USING COMBINED METHODS OF NON-DESTRUCTIVE TESTING TOGETHER WITH TRADITIONAL ONES

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ABSTRACT
The aim of this paper is the definition of a method to assess old timber structures, based on the analysis of systematic data gathered at ancient buildings, about the characteristics of the wooden structural elements. Degradation factors lead to the loss of structural integrity and serviceability of timber structures, in the absence of appropriate maintenance interventions. Non-destructive testing is applied, together with traditional methods, with the aim of not damaging existing structures during the surveying process. These structures are part of historic buildings, and should be conserved, when possible, with the maintenance of the load bearing function. This is a purpose that must be considered by the architect or other technician, responsible of building conservation.

The lack of a helpful and reliable inspection method to detect decayed parts of the timber structural elements, undoubtedly caused its replacement in a substantial amount of historic buildings. The proposed method following described, was developed on the basis of several years of experience both in scientific research and on building site inspections. The authors belong to a research group developing at the moment an I+D+i Project, (Ministerio de Fomento, Spain, 2004) The objective of this project is to define a method of assessment of historic buildings by using non destructive testing. A method for NDT evaluation of timber structures, together with visual inspection, and a minimum of destructive testing (just to determine a few parameters) to obtain conclusions about the structural elements mechanical characteristics, is presented. The instruments applied in situ are micro drilling, ultrasonics and wood hardener. NDT are useful techniques to shorten the time to arrive to a diagnosis, and minimize causing damage to the sound timber. Additionally, the condition of the structure during its lifetime can be monitored with repeated measurements at inspection points marked on the surface of the members, or even critical parts of the structure can be examined more closely.

INTRODUCTION
Historic timber structures must be conserved, maintaining its structural function as much as possible, without substitution of timber elements, but always considering safety aspects for the occupants of the building. For that purpose, an accurate assessment is necessary, considering the serviceability of the complete structural design and the individual timber elements.

Wood, as an organic material, is susceptible of degradation, produced by rot and insect attach, and also, by fire action. To evaluate the material degradation extension, different methods may be applied: traditional ones, destructive and non-destructive testing.

A method has been developed by this research group, by combining traditional methods of inspection and non destructive testing (NDT). Microdrilling, ultrasonics and wood hardener are the non-destructive instruments used *in situ* for this purpose. Interesting conclusions came out, which are presented in this paper. This method is suitable, as well, for monitoring the condition of historic timber structures during its lifetime. This inspection may be punctual in determined timber elements of the structure or in some critical parts of it.

BUILDING BACKGROUND SURVEYING

Previous information must be gathered about the building origin, posterior development, refurbishments, extensions or other interventions during its lifetime. Material quality, its decay, the original construction system and detailing, former chemical treatments applied for its conservation, and any other aspects involving structural movements of the structure (not only the timber ones) are aspects to be considered. Without this information no coherent diagnosis can be made, because the interpretation of pathology may be disguised. Information about timber construction systems is available nowadays, as a result of the development of the research done in Construction History [1].

Other important aspects to be taken in to account for timber structures conservation are: a) the consideration that ancient buildings were not always built by expert constructors, so original defects in the construction system can be detected; b) the other aspect to consider is the wrong criteria of some technicians and architects about re-using an existing building, when it is seen as a huge container where all uses can be developed in it, increasing bearing loads that produce negative effects for is conservation.

THE METHOD DEVELOPED

Based on previous NDT research developed by this work team, a method for timber structures assessment was traced. The first step to solve is to clarify with the client/owner of the building, which are the objectives of the assessment, in order to know which are the questions to be answered. Once the problem is defined, several posterior phases must be developed. These are as follows:

- Analysis of existing documental and graphic information, to establish the structural design and its evolution
- Visual inspection, for wood identification, determination of its quality and possible biological attach
- Destructive testing, to precise wood density and anatomic identification. Eventually may be useful to determine dendrochronology. (ϕ5mm probes are enough for this purpose).
- NDT methods of inspection, to gather information about mechanical characteristics and damage extension of the material, including determination of moisture content by means of a hygrometer.
- Data analysis
- Structure evaluation

PREVIOUS NDT LABORATORY RESEARCH

Al NDT instruments were tested on the building site by this research group, together with visual inspection, at the same time that bibliography about this subject was analysed. After this experience, it was detected the necessity to compare the information given by each one of the instruments used on the building site, to optimize results and time consuming. For this purpose it was determined that several wooden probes coming from a discarded timber structure, will be tested at the Laboratory. Five old timber beams were selected to obtain probes from its endings. This number was considered enough to compare the data given by the different NDT instruments, at the same time that it was possible to do an intense visual inspection, defining annual rings direction, its width, regularity, knots presence, and any other organoleptic characteristic of the material

All probes were of *pinus sylvestris*, which is the wood specie extensively used in ancient building construction at Valencia. These probes were identified, drawn and photographed, previously the testing was developed. A grid was traced to define the position of microdrilling, ultrasonic auscultation and hardener testing (Fig. 1). Small probes gave, at least, 16 points for microdrilling, 6 ultrasonic auscultation points and 8 wood hardener testing.

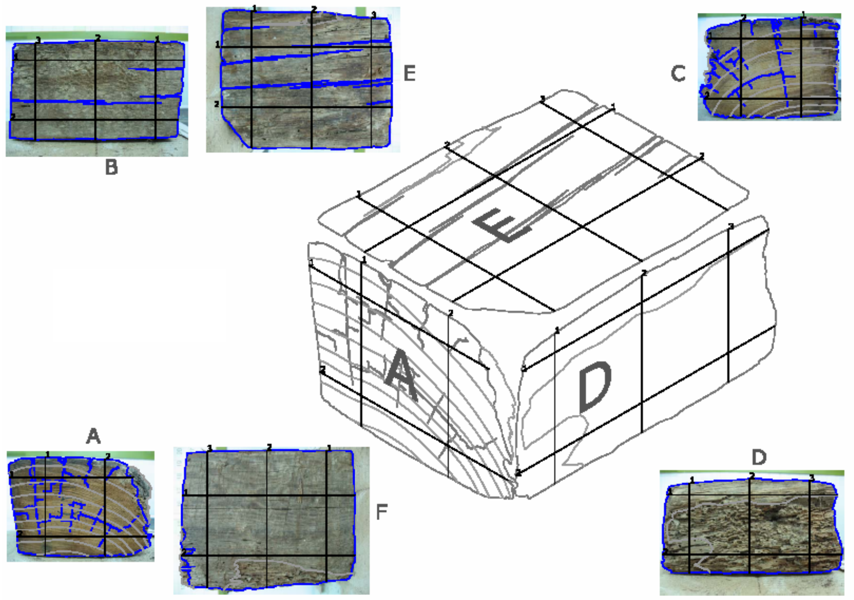

Fig. 1. Drawing of the probes, in this case Probe 5, showing grid for microdrilling

Ultrasonics

Is a NDT widely applied to the study of concrete, stone and wooden elements. It is based on acoustic properties of the different materials. Allow to make an approach to the dynamic elasticity modulus value, as the velocity of sound propagation is in relation with mechanical properties. The module obtained by this equation is 5% higher than the determined by bending test [2]:

$$E= v2\ \rho \qquad (1)$$

being *E* dynamic elasticity modulus; *v*, sound propagation velocity in wood; ρ, its density.

Wood Hardener Tester, Pilodyn,

Is a portable tool for estimating wood hardness, by measuring the depth penetration of a 1,5 mm diameter pin, which is shot into the outer millimetres of the timber element, with a constant force. The depth of the pin penetration varies in function of the material consistency. It is very useful for a quick investigation of the surface consistency of a timber element [3]. Because of the superficial information given, is only possible data about its density and superficial insect attach.

Microdrilling

Resistograph, consists of a 1,5 mm diameter drill probe, that penetrates up to 45 mm into the timber element. The force employed by the motor varies to give a constant velocity of penetration. These variations are due to the different consistency of the annual rings, knots, holes, decayed material, describing a graphic 1:1 scale, in which the interior of the element can be observed [4]. This is very valuable to determine the extension of certain attach, previously identified by visual inspection (Fig. 2 and 3). Each probe was tested in all directions, giving data of at least 6 points in the larges faces and at least 4, in the smaller ones.

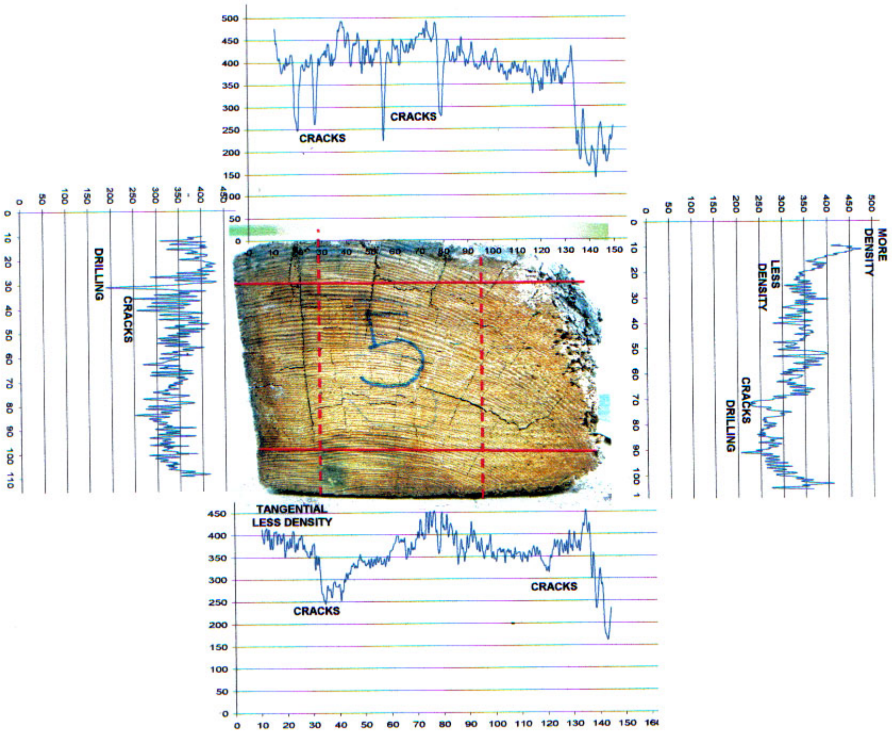

Fig. 2. Some of the microdrilling graphics obtained in probe 5

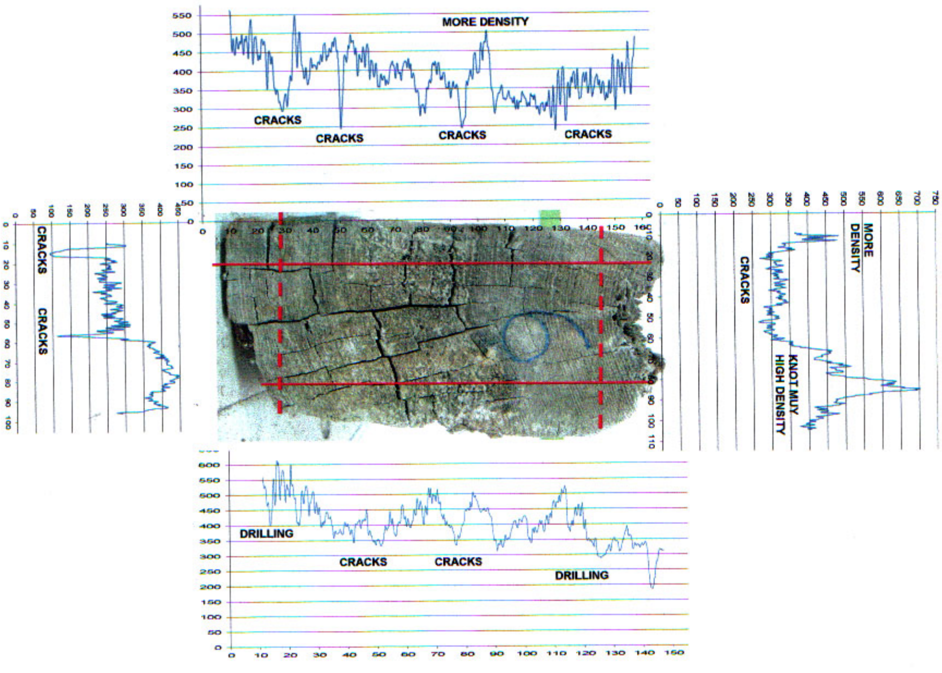

Fig. 3. Some of the microdrilling graphics obtained in probe 6

The possibility to detect discontinuities and wood density or consistency changes through the timber element cross section is evident, after observing the probes and the graphics obtained by microdrilling. It was not possible to find any relationships between ultrasonics with mean values of microdrilling testing.

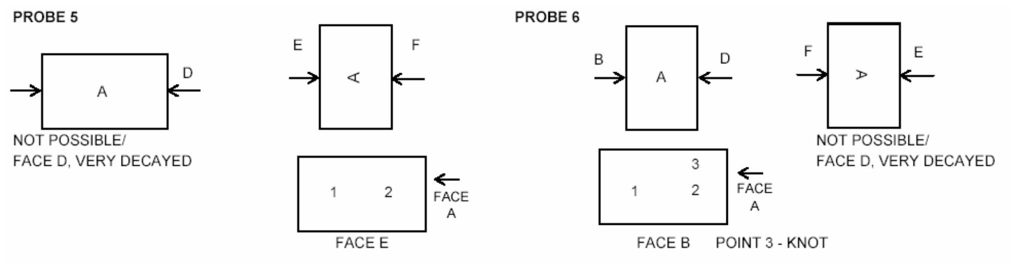

Fig. 4. Scheme of ultrasonic testing in probes 5 and 6

Ultrasonic testing allowed determining the relation between radial and tangential values of sound velocity in wood, respect with axial direction (Table 1). Considering the mean density values of the wood specie, belonging to its structural quality [5], an approximation to the dynamic MOE, and MOE was possible. These values are shown in Table 2

WAVES DIRECTION	**% RESPECT OF AXIAL DIRECTION**
R	24,45
TG	39,36
TG/R	28,62

Table 1. Sound velocity variation depending on the wave direction.

PROBE	**VELOCITY (m/s)**	**DENS (kg/m$^{3)}$**	**MOE DYNAMIC (N/mm^3)**	**MOE (95%)**
1	4496,34	435,00	8794,41	8354,69
3	5173,82	435,00	11644,26	11062,04
4	5054,92	435,00	11115,23	10559,46
5	5230,77	435,00	11902,01	11306,91
6	5098,61	435,00	11308,20	10742,79

Table 2. Approximate MOE values

Pilodyn testing is very valuable when determination of surface consistency is necessary. Schemes of Pilodyn testing of probes 5 and 6 are shown in figure 4.

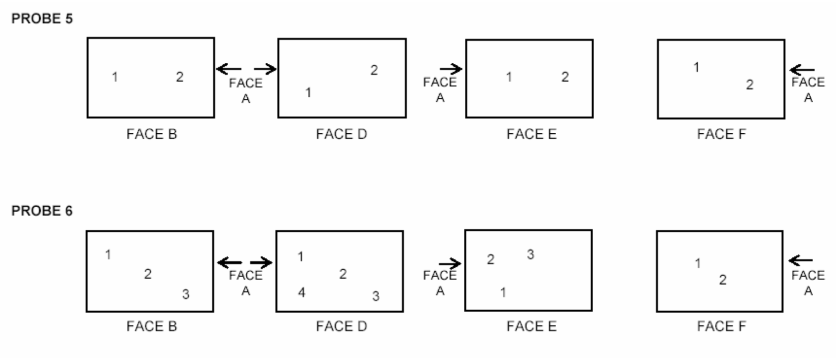

Fig. 5. Scheme of probes 5 and 6 for wood hardener testing

Some conclusions were obtained comparing mean values with the wood hardener results and the first millimetres mean values of microdrilling, as shown in figures 6, 7 and 8.

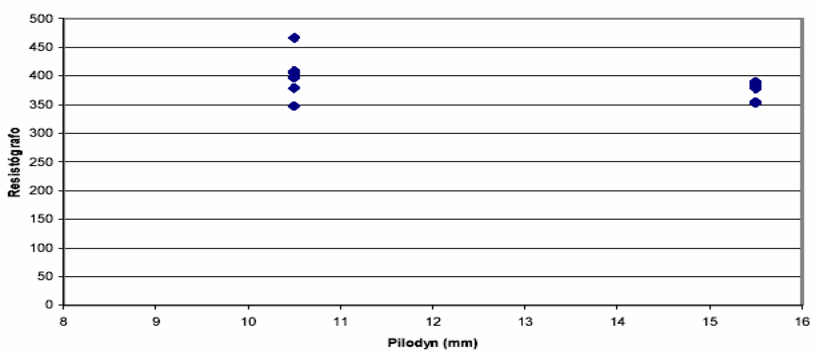

Fig. 6. Microdrilling mean values-Pilodyn, of probe 5

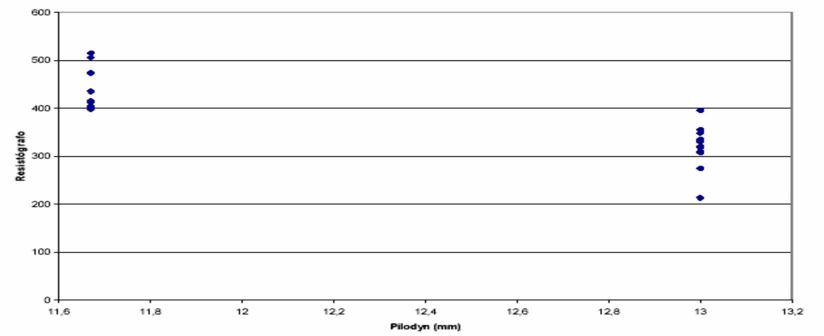

Fig. 7. Microdrilling mean values-Pilodyn, of probe 6

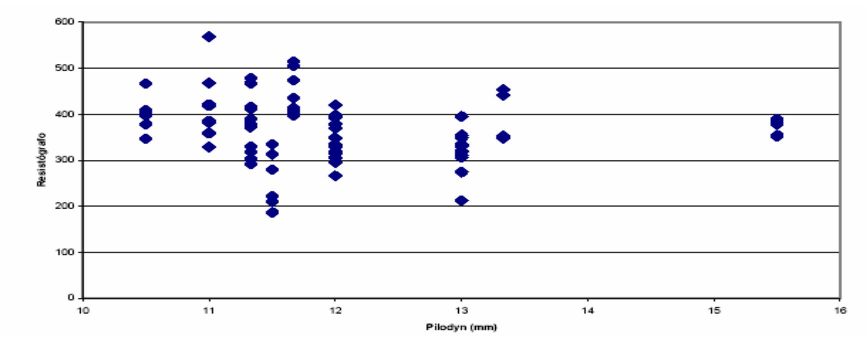

Fig. 8. Microdrilling mean values-Pilodyn, of all probes

	PILODYN MEDIA (por 1000)	AXIAL VELOCITY	MOE DIN
PROBE 1	1200	4496,34	8794,41
PROBE 3	1075	5173,82	11062,00
PROBE 4	1162,5	5054,92	11062,04
PROBE 5	1050	5230,77	11902,00
PROBE 6	1175	5098,61	11308,20

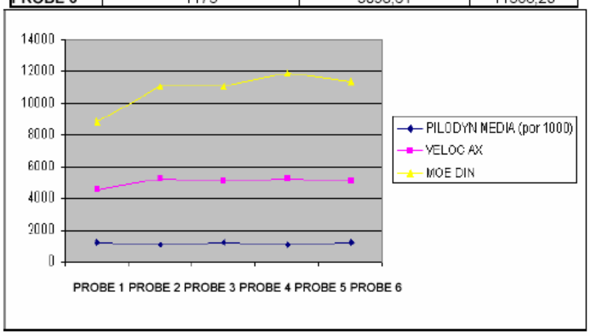

Table 3. Relation between Pilodyn tester-sound velocity and MOE din

As a result of this testing on probes, some conclusions came out. There is a statistic relation between mean values determined by Pilodyn testing (impact resistant, in millimetres of penetration) and microdrilling (depth resistance of the drilling). The value interval belonging to each drilling is of a wide range. It is an inverse relationship between each testing, as one of them is giving data of the resistance to impact, that will be higher when wood have less consistency, and microdrilling values are lower when wood quality is in worst condition.

In a timber element enough homogeneous, there will be established an inverse correlation between length of penetration of the wood hardener tester, and the mean value of the microdrilling for the same depth. The slope of the lineal correlation will depend on the considered material. In case of wooden elements, the direction of the annual rings respect of the faces is an important aspect to be observed. This correlation is possible to determine with a great number of data gathered in the same material and element.

These first conclusions allowed considering the adequacy of a testing method under the aspects mentioned before. Three case studies were done, based on these conclusions [6].

CASE STUDY: VILLA IVONNE. MELIANA

After the former experience done to prove the method of assessment, an old building was studied extensively. In this case the building is "Villa Ivonne", located at Meliana, close to Valencia City. The last owner was the Nolla family, producers of ceramic pavement during XIXth century. Probably it is a XVIth century building, lately refurbished and enlarged, because of its design, the composition of walls and construction system. It is a two storey building, with *pisé* and stone walls, timber floors and roof structure. The building has a two sloped roof, built with timber rafters with the ridge beam leaning over a central wall. The rafters are 10 x 20 cm in section.

The wood spice was identified *pinus sylvestris*. Its quality was defined as follows:

- Knots, 5 cm diameter, separated 35-40 cm, being its size less than 1/5 the height of the timber elements and less than 2/3 its width.
- No cracks were present, except punctual cases.
- Fibre deviation was observed in some timber elements.

White wood was found on the upper side of rafters, being this one, the most decayed area.
The wood quality was established as ME-1 based on UNE 56544:1997; Resistant class C24.
Characteristic bending resistance 24 N/mm^2, MOE axial 11 kN/ mm^2; characteristic density 350 kg/m^3.

Decay Observed in Visual Inspection

It was observed a general insect attach of common beetle, long horn beetle and termite attach, and wood rot as well. All data was gathered in Tables, and later analysed. Because of the extension of this information, only is presented data of room 3A (Table 4).

Instrumental Analysis

Based on the previous research done at the laboratory, and after several case studies where the method was applied, several measurements were obtained in order to gather the necessary information for the assessment.

The instrumental analysis done was:

- Moisture content, in all elements
- Ultrasonics, in all elements
- Microdrilling, one each three elements, and where alterations were detected
- Pilodyn (wood hardener tester), in all elements

The information about the timber roof structure of room 3A, can be seen in Table 4, later presented in a plan, indicating the alterations detected.

MELIANA - ROOF

ROOM	JOIST	MOISTURE % ENDING			MOISTURE % VERT	WIDTH	HEIGHT	PILODYN ENDING			ULTRAS.	MICRODRILLING	PATHOLOGY	
		VERT	RIGHT	LEFT	CENTRE	(cm)	(cm)	VERT	RIGHT	LEFT	(µs)	(ENDING)	INFERIOR ENDING	SUPERIOR ENDING
3A	1A	-	-	-	-	12	22	-	-	-	-	-		
NORTH	1N	24,6	25,3	23,8	14,2	12	20	10	-	15	-	orden 110 vert		
	2N	15,2	24,8	16	11,8	10	20	12	14	14	63,5	-	REINFORCED IN 3/5 CENTRAL PRTMETALLIC PROTHESIS. TL	TR
	3N	23,9	16,5	19,3	12,6	12	21,5	11	11,5	12	64,5	orden 111 vert		
	4N	21	22,5	19,1	13,1	11	22,5	11	13	13	53,5	-	FEW KNOTS	
	5N	12,2	12	13,7	13,6	12	21	13,5	15	14	67,1	-	MANY KNOTS. RESINOUS TERMITE ATTACH	TL
	6N	10,4	12,6	10,2	13,6	10,5	22,5	18	12	14	52,9	orden 112 vert	ROT ENDING	
	7N	14,9	12,7	12,2	13,9	12	21	12	16	17	-	-	BROKEN JOIST	
	8N	13,8	14,8	16	13,1	11	22,5	13,5	14	17	52,7	-	TL. COMMON BEETLE ATTACH	TL

SPECIE OF WOOD
PINUS SYLVESTRIS

QUALITY
STRAIGHT GRAIN
KNOTSØ 5 cm, SEPARATED 35-40 CM
WHITE WOOD ON UPPERSIDE OF THE RAFTER
COMMON BEETLE
LONG HORN BEETLE
WOOD ROT IN ENDINGS

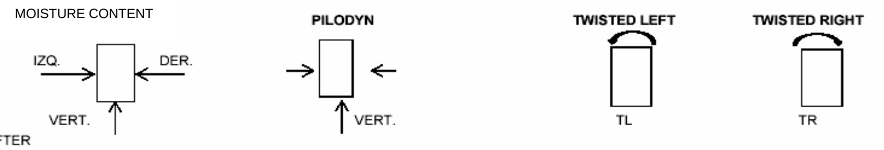

Table 4. Data chart of timber elements at room 3A

Information of all the structure was obtained and analysed, but in this case are presented data about this room, in Tables 5 and 6.

TIMBER ROOF STRUCTURE		RESIST – PILODYN	
RAFTER	**PILODYN**	**R – MEAN**	**R – MÁX**
SALA 3A (NORTE)			
1N	10	216,4585415	239
3N	11	248,6911898	377
6N	18	263,6163243	336

Table 5. Data values of Pilodyn tester and Resistograph

TIMBER ROOF MELIANA
ROOM 3 A NORTH

WIDTH (cm)	ULTRAS. (µs)	VELOCITY	VELOC. TG	VELOC. TG MEAN	VELOC AXIAL	DENSITY	MOE kN/mm^2
10	63,5	1574,80315					
12	64,5	1860,465116	1860,465116	1955,415819	4888,539548	320	7,647302051
11	53,5	2056,074766	2056,074766				
12	67,1	1788,375559	1788,375559				
10,5	52,9	1984,877127	1984,877127				
11	52,7	2087,286528	2087,286528				

Table6. Data values of ultrasonic testing

Visual inspection was valuable to identify the wood spice, the biological attach and the damage extension. The same correspondence of Pilodyn with resistograph mean values was found, as in case of the probes testing. Ultrasonics testing was a valuable instrument to give an approach to the wood MOE. With this information, the structure can be easily evaluated. Mechanical characteristics of wood are below the values given for the timber classification as C24. Structural evaluation can be done using MOE 7,64 kN/mm^2.

CONCLUSIONS

After the development of the research project, and applied to this case study, some conclusions came out:

- Not only the material or the individual timber element must be studied, but also the whole structure, to give the correct answer to the problem.
- Timber structure analysis is possible when NDT is applied, allowing to quantify the theoretical resistance of the timber elements.
- Visual inspection can not be substituted by any other method of inspection. It must be the starting point of the surveying.
- There exist correlations between bending strength, MOE, ultrasonics in axial direction, wood hardener and mean/max values of microdrilling that came out of former research works, as seen in the bibliography. The results of our investigation agree with those results.
- Each NDT can be used of a certain purpose. Microdrilling may be used to "observe" the interior of the wooden beam, but a fast information can be gathered by using ultrasonics and wood hardener testing.

ENDNOTES

1. Several institutions and societies are studying the development of construction systems. There are important periodical events dedicated to these themes, as the International Congress on Construction History, between others. There are many historical construction treatises, and specific monographs treating these themes, as are shown in the bibliography.
2. It must be consulted all the work done by V. Bucur, about the characteristics of wood in relation with sound propagation velocity in this material. Also see Sandoz, and recent works of Machado and Basterra, cited in the bibliography,
3. Interesting results came out of the investigation prepared by Giuriani and Gubana, cited in the bibliography. Also see A. M. Korzenlowski y W. Dzbenski works.
4. A recent PHD Thesis was presened at Valencia, *Métodos de ensayos no destructivos para la estimación de las propiedades físicas y mecánicas de las maderas*, done by Rafael Capuz Lladró, under the direction of Dr. Javier Benlloch Marco and Dra. Eva Hermoso Prieto, UPV, September 2000, with precise results about microdrilling data analysis. Recent works were done by Casado, and Lauriola, cited in the Bibliography.
5. After the structural classification of the wood spice used for the NDT testing, it was determined as C18, ME-2, with a mean density of 435 kg/m^3 (UNE 56544, CTE). This is based on an extensive testing prepared on *pinus sylvesrtis* probes by Arriaga and Esteban.
6. The former experience applying this method with satisfactory results were two roof structures, one at a school established in an ancient building in Valencia City and another one at the main house of Alcira City, 30 km south from Valencia City, and timber floor structures at Betxí Palace, in Castellón.

BIBLIOGRAPHY

1. Alberti, L. B., *De re aedificatoria*, Florencia 1485, traducida por M. Alonso Gómez, 1582, Re-editada por Albatros Ediciones, 1977.
2. Arriaga, F., Esteban, M., "Evaluation of load carrying capacity of old timber structures", *Proceedings of the 8th Conference on Timber Engineering (WCTE 2004).* Finnish Association of Civil Engineers (RIL), VTT Technical Research Centre of Finland and Wood Focus, Lahti, Finland 14-17 June 2004.
3. Arriaga, F., Esteban, M., Relea, E., Evaluación de la capacidad portante de piezas de gruesa escuadría de madera de conífera en estructuras existentes, *Materiales de Construcción*, vol 55, nº 280 43-52

4. Basterra, A. et alt., “Análisis de las técnicas de diagnóstico de madera estructural en edificios existentes y propuesta de integración orientada al proyecto”, *I Jornadas de investigación en construcción,* Instituto de Ciencias de la Construcción “Eduardo Torroja”. 2005
5. Basterra, A., Ramón, G., Barranco, I, López G., “Evaluación preliminar de la estructura de madera de quince (12+3) monumentos declarados B.I.C. en Castilla-León”, *Cimad’04 – A Madeira na Construção, 1.º Congresso Ibérico,* Guimãres, 2004
6. Binda, L, Cantini, L., Condoleo & Saisi A., “Non-destructive testing techniques applied to the masonry and timber structures of the Crocifisso Church in Noto”, *Stremah 2007,* WIT Press, 2007
7. Bucur, V., Acoustics of wood, CRC, 1995
8. Casado, M, et alt, “Determinación de la capacidad resistente mediante métodos no destructivos. Aplicación en viguetas de forjado de un edificio singular”, *IV Congreso Forestal Español*. Zaragoza, September de 2005
9. Demaus, Robert, *Non-Destructive Investigation*, Buildingconservation.com, 1996
10. Feio, A.O., Machado, J.S. y Lourenço, P.B, “Caracterização de propiedades da madeira de castaño na direcção perpendicular ao fio - Recurso a técnicas destrutivas e não destrutivas de ensai”, *Cimad’04 – A Madeira na Construção, 1.º Congresso Ibérico,* Guimãres, 2004
11. Fernández Cabo, M., *Armaduras de cubierta*, Valladolid, 1997
12. Fr. Lorenzo de San Nicolás, “Arte y uso de arquitectura”, Madrid, 1639 y 1664. Re-edición Madrid Albatros, 1989
13. Giuliani, E, Gubana, A., “Ensayo de penetración, para evaluar el deterioro de la madera, y su aplicación al monumento Loggia”. Departamento de Ingeniería Civil, Universidad de Brescia, Vía Valotti 9, 25133 Brescia, Italia *Materials and Structures*, 1993, 26, 8-14
14. Jorissen, A., “The Dutch Pavillion at the EXPO 2000 in Hannover”.
15. Korzenlowski, A., Dzbenski, W., “Estimación de las Propiedades Mecánicas de Maderas Estructurales de Conífera, Mediante Ensayos de Dureza por Impacto”, *Facultad de Tecnología de la Madera*, Universidad Agrícola de Varsovia.
16. Lauriola, M; Mannucci, M; Oschi, M; “A reliable inspection procedure of existing timber structures: the case of Guarini’s timber roofs. Racconigi castle (Italy)”. *Istituto per la ricerca del legno*. Fienze. Via Barazzuoli, 23. Firenze.
17. Machado, “Strength appraisal of wooden members in service by combining new and old technology”, *Stremah 2007,* WIT Press, 2007.
18. Mainstone, R., *Development of structural form,* Harmondsworth, Middesex : Penguin Books, 1983
19. Nuere, E., *La carpintería de armar española*, Munilla-Leria, 2000
20. Palaia, L., et alt., *La conservación de la madera en los edificios antiguos*, Valencia, 1998.
21. Palladio, A., *I Quattro Libri dell’Architettura,* Venecia, 1570, Reeditado por Ulrico Hoepli, Milano, 1968.
22. Pariset, Jean-Daniel, *Charpentes de la Région centre du XII au XIII siècle*, Paris, 2002
23. *Proceedings of the First International Congress on Construction History*, Madrid, 20th-24th January 2003, Instituto Juan de Herrera, Madrid, 2003. Three volumes.
24. Serlio, S., *Tercero y cuarto libro de arquitectura,* Edición facsimilar Colegio oficial de aparejadores y arquitectos técnicos de Asturias, Oviedo 1986,
25. Singh, J., *Environmental monitoring and control.* Buildingconservation.com.
26. Tampone, G., *Il restauro delle strutture di legno,* Editore: Hoepli, 1996
27. Uzielli, L., *Il manuale del legno strutturale,* Editore Mancosu, Roma, 1991
28. Vitrubio Polión, M., *Los Diez Libros de Arquitectura*, Traducidos del latín y comentados por Joseph Ortiz y Sanz, Madrid 1787.

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