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IN SITU ASSESSMENT OF STRUCTURAL TIMBER ELEMENTS OF A HISTORIC BUILDING BY MOISTURE CONTENT ANALYSES AND ULTRASONIC VELOCITY TESTS

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ABSTRACT

The Moisture content analyses (MC) and the ultrasonic velocity measurements (UVM) promise to be particularly important to assess the state of deterioration and the adequacy of the boundary and microclimatic conditions for timber elements when applied to a building with an important artistic and historical value. These nondestructive evaluation (NDE) methods supported by laboratory analyses of timber samples were applied in the inspection of a 16th century housing building, Corral del Conde in Seville, Spain. The methodology used was the non-destructive testing for determination of moisture content and measures from the times of transmission of ultrasonic waves to detect internal defaults. This methodology allows establishing the diagnosis of a wooden structure, obtaining an estimate of the degree of impairment of the same, and assessing the bearing capacity of timber elements for rehabilitation works. The combined interpretation of the results was done to assess the condition of structural timber elements in terms of their state of preservation, the dampness problems and the recent incompatible repairs affecting them. Results indicated that moist areas in the structure were associated with ground and roof drainage problems. Juxtaposition of the MC and UVM together with laboratory analyses was found to be useful to assess the different states of deterioration of timber, enhanced the accuracy and effectiveness of the survey and facilitated to build up the urgent and long-term conservation programs.

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Key words: Ultrasonic velocity measurement, non-destructive testing, moisture content analyses, historical timber structures.

Introduction

The building presented as a case study, the "Corral del Conde", is a 16th century building, located in the city centre of Seville (see Fig. 1). It was declared National Monument of Historical Artistic Cultural Interest (BIC) in 1979 and the apartments suffered a full rehabilitation in 1993 but present nowadays a much deteriorated state due to inadequate construction systems used in the refurbishment works. The restoration of an historical building requires technical and historical investigation in order to assess its main architectural features and the effects superimposed by its history. The study of the structure and construction details through historical, archival and bibliographical documentation is useful to characterise, analyse and record the origin of the structure and the vicissitudes during its history. Geometrical and material surveys and nondestructive evaluation (NDE) tests were performed in situ to evaluate the level of damage in timber structures.

Figure 1: General view and detail of the exposed timber structure of the building.

The use of timber 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 neither fire (Rome under Nero in 64 after JC, London in 1666 after JC) nor biological attacks appear (the main sources of wood degradation), many secular constructions still 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 [1]. These properties are the basis for any design using the material and are defined in the standards. For example, in Europe, the EN338 norm [2] relates the mechanical properties for sawn timber.

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

In rehabilitation works of ancient timber structures, in situ inspection and evaluation of mechanical properties represent a first step towards diagnosis, structural analysis and possible remedial measures. Structural assessment comprises the need for answers regarding strength of sound timber elements, as well as regarding the effect of local damage due to biological attack (usually associated with excessive moisture). NDE plays a key role here, usually adopted for qualitative evaluation. Gradual steps towards quantitative evaluation have been made recently since the removal of samples and their destructive testing is time-consuming, unpractical and, often, even not feasible.

The efficiency and reliability of NDE methods can be increased if extensive laboratorial tests are used to provide correlations with the mechanical characteristics of wood [3, 4]. In particular, the last decades witnessed developments in the NDE techniques, equipments and methods that allow increasing their accuracy. NDE can be grouped in Global Test Methods (GTM) and Local Test Methods (LTM) [5, 6]. The former includes e.g. the application of the ultrasonic and vibration methods [7, 8]. The latter plays usually a leading role in the support of visual inspection, being the Resistograph [9] and the Pilodyn [10] the most common techniques. The general characteristic of all methods is their easy usage and transport, plus the fast in situ application.

The characterization of wood can be done effectively by NDE methods that do not require the extraction of test specimens, since the element or structure, rather than a specimen, is evaluated. At a microscopic level, energy storage properties are controlled by cell orientation and structural composition, which are factors that contribute to the material static elasticity. These properties can be observed as vibration oscillation frequency or sound velocity transmission. Thus, measurements of the deterioration rates of free vibrations or acoustic wave attenuation are used to examine the property of energy dissipation in wood.

NDE methods offer advantages over conventional wood characterization methods, such as the possibility of evaluating the structural integrity of an element without extracting test specimens, faster analysis of large populations, and versatility to adapt to standardized production line routines [11].

NDE is an important tool for the characterization of wood [12] and can be used in industry to improve process quality control through a greater uniformity of the raw material and its by-products.

Another application of the NDE methods is the evaluation of structures that are in use, i.e., in situ evaluation, allowing for their maintenance or rehabilitation through a mapping of the deteriorated areas, which permits evaluations to be made of their structural integrity without the need to remove part of the structure.

<u>Ultrasonic Tests</u>

The propagation of ultrasonic waves in wood depends principally on the mechanical properties of the cell wall. The cell wall density is reasonably constant, but the modulus of elasticity varies owing to variations in the cell wall structure; hence, one can expect a range of values for the velocity propagation property [13]. The relationship between ultrasonic velocity, density and stiffness is:

$$V = \sqrt{\frac{C}{\rho}}$$

Where C is the stiffness modulus; ρ is the density of the wood and V the velocity of the longitudinal wave.

The factors that influence the propagation of ultrasonic waves in wood are physical properties of the substrate, geometrical characteristics of the species (macro and microstructures), conditions of the medium (temperature, humidity) and the procedure utilized to take the measurements [14] (frequency and sensitivity of the transducers, their size, the position and dynamic characteristics of the equipment).

The ultrasonic velocity through wood varies with moisture content even above the fiber saturation point [15, 16]. The nature of the response of ultrasonic velocity to moisture content changes led us to conclude that moisture gradients during drying have a dominating effect.

The ultrasonic tests were carried out using the equipment Pundit/Plus, with cylinder-shaped transducers of 150 kHz. Although three methods were used in the framework of a more general approach, (indirect method; direct method parallel to the grain, and direct method perpendicular to the grain), the only method reported in this paper is the direct method, since it is the most appropriate in practical cases. The direct method can be used for evaluating different zones of the element, it gives a local evaluation of the element but it needs access to two opposite faces of the element. Regarding the direct method parallel to the grain, it requires access to the ends of the elements (in most cases not possible) and allows only a global evaluation of the material (it is not possible to evaluate weak or critical zones in the element).

The transmission technique of elastic waves based on the direct method was used in all the faces. For the case of radial and tangential tests specimens, the transducers were used in two opposite faces, depending on the orientation of annual growth rings, see Fig. 2 and Fig. 3. In all tests a constant pressure was applied by means of a rubber spring, allowing adequate transmission of the elastic wave between the transducers and the specimen under testing.

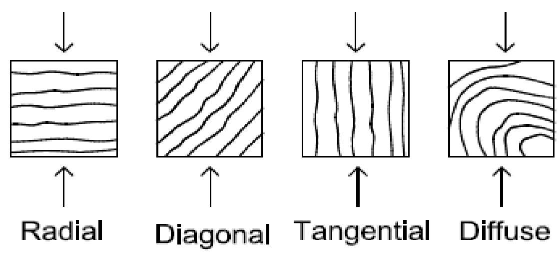

Figure 2: Rings orientation with respect the loading direction.

Figure 3: UV measurements to in faces A-A´.

The transversal mode is mainly used for the local singularities detection. This mode is based on comparative measurements: decayed area is compared to a supposed sane area in order to valuate 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 Figures 4 and 5. 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.

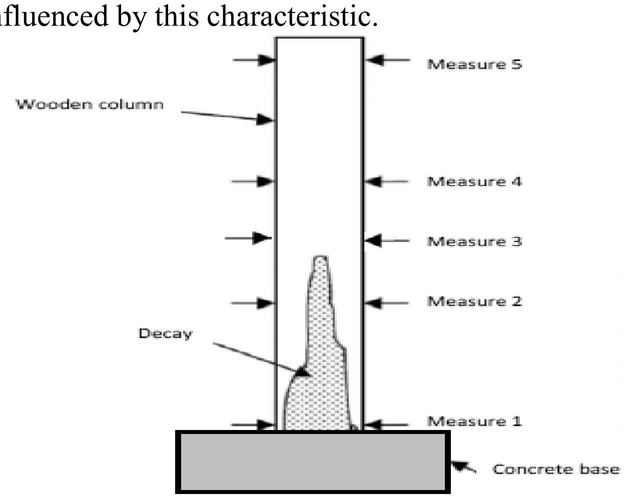

Figure 4: Comparative measurements in height.

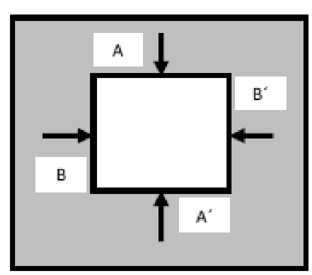

Figure 5: Different measurements orientations.

With the results obtained, the nature of the singularity can't 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, see Fig. 6 and Fig. 7.

Figure 6: Biological decay at the element´s base.

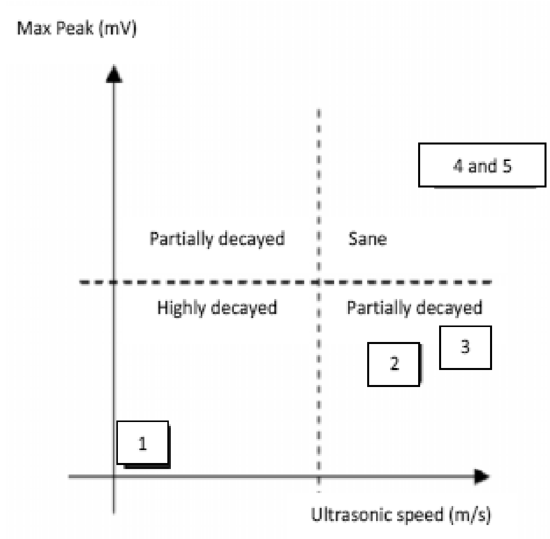

Figure 7: Measurements classification in the five different heights.

<u>Moisture Tests</u>

The moisture tests were carried out using the Neurtek equipment Protimeter Timbermaster that is a simple to use wood moisture meter specifically designed for the timber industry. It is ideal for a range of quality control applications associated with the production, trading and use of wood products. This instrument has eight calibration scales, enabling the user to take accurate moisture measurements in 150 wood species. When necessary, it can be used with a temperature probe that automatically corrects the measured moisture level with respect to the temperature of the wood being tested. MC analyses were done in the in situ elements and also in laboratory samples analyzed under different relative humidity conditions. Researchers [13, 15–19] conducted several studies on the relationship between ultrasonic velocity and moisture content. Most of these studies were conducted such that the dry shell and wet core were in series to the direction of sound transmission. As applied to kiln control, this arrangement would correspond to measuring ultrasonic velocity through the thickness of a wide board during drying. A range of relationships was found depending on species. In most species, the increase in velocity from green to the fiber saturation point was not very large. However, the increase in velocity from fiber saturation to 0% moisture content was much greater [17].

The use of ultrasound for monitoring the moisture content in wood is relatively new [13]. The ultrasonic velocity decreases with moisture content, whereas the attenuation increases with increasing moisture content. The maximum velocity and the minimum attenuation were measured at laboratory in dry conditions. At low content (U<18%), when the water is present in the cell walls as bound water, the ultrasonic pulse is scattered by the wood and by cell boundaries. The side units of OH or other radicals of the cellulosic material may reorient their position under the ultrasonic stress. In this case the attenuation mechanism related to the cellulosic cell wall material is probably the most important. At higher moisture content but under the fiber saturation point, the scattering at cell boundaries could be the most important loss mechanism. After the fiber saturation point, when free water is present in cellular cavities, the porosity of the material intervenes as a predominant factor in ultrasonic scattering [13].

Results and Discussion

During the laboratory analyses, fifteen timber samples were studied consisting of some pine species (Pinus sylvestris and Pinus pinaster). Their equilibrium moisture content (MC) and ultrasonic velocity values (UV) were examined for 56%, 75% and 90% relative humidity (RH) conditions during the periods of moisture absorption and desorption. MC of timber samples was determined by recording the increase and decrease in weight. According to the laboratory analyses, MC of timber samples was found to be in the range of 6.1–22.8% at 56%, 75% and 90% RH conditions. The protimeter readings done at the surface of the in situ samples gave correlative MC readings than those determined in the laboratory by weight measurements. During the In situ tests over 3000 UV and MC measurements were taken in over 200 timber pillars alongside the building. Table 2 shows the range of moisture content (MC) for the pillars analyzed. It is easy to check that higher MC percentages correspond to the lower level. Ground floor measurements show that over 90% of the pillars have MC >10%, while in the second level only a 6% of the have MC >10%.

Table 2: Analysis of moisture content (MC) values.

	Number of specimens			% of specimens per level		
Percentages	LEVEL 0	LEVEL 1	LEVEL 2	LEVEL 0	LEVEL 1	LEVEL 2
<7%	0	13	8	0%	18%	15%
7-10%	6	53	43	8%	72%	80%
10-15%	33	8	3	46%	11%	6%
>15%	32	0	0	45%	0%	0%
	71	74	54	Total specimens		

In situ UVM tests for the 200 pillars over 3000 are shown in Table 3. The results shown for every pillar depend on the height of the test. Over a total height of 2,5m for every timber element, measurements have been taken at five different heights (0.1 m, 0,4 m, 0.8 m, 1.2 m and 1,6 m) for the ground floor level. For first and second levels three different heights (0.1 m, 0.8 m and 1,6 m) have been tested.

According to other researchers [20] from the correlations obtained after tests conducted in the laboratory on samples of the same species of wood: Pinus sylvestris and Pinus pinaster, with varying degrees of deterioration two intervals have been established for the diagnosis of this type of wood: (perpendicular to grain) normal speed > 1400 m/s: healthy wood; normal speed < 1400 m/s: decayed wood, associated with loss of density and loss of resistance values. In this case a 24% of the ground floor pillars present a high decay state in the basement of the pillar but superior areas of the same pillars present a reasonable state of preservation except for 3 of them. Nearly 80% of the pillars of the first and second levels present a reasonable state of preservation for the whole length of the pillar.

Table 3: Analysis of ultrasonic velocity (UV) values (m/s).

	Number of specimens										
	GROUND LEVEL					LEVEL 1			LEVEL 2		
Height (m)	0,1	0,4	0,8	1,2	1,6	0,1	0,8	1,6	0,1	0,8	1,6
Not meassurable	2	0	0	0	0	0	0	0	0	0	0
0 – 700 (m/s)	0	0	0	0	0	0	0	0	0	0	0
700 – 1400 (m/s)	17	3	5	1	3	6	3	5	3	2	0
1400 – 2100 (m/s)	52	64	62	61	58	59	57	52	42	41	44
2100 – 3000 (m/s)	0	4	4	9	10	9	14	17	9	11	10
Total pillars (units)	71	71	71	71	71	74	74	74	54	54	54
	% of specimens per level										
Not meassurable	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
0 – 700 (m/s)	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
700 – 1400 (m/s)	24%	4%	7%	1%	4%	8%	4%	7%	6%	4%	0%
1400 – 2100 (m/s)	73%	90%	87%	86%	82%	80%	77%	70%	78%	76%	81%
2100 – 3000 (m/s)	0%	6%	6%	13%	14%	12%	19%	23%	17%	20%	19%

Conclusions

The combined interpretation of the in situ UVM and MC tests together with laboratory analyses gave information on the condition of structural timber elements in terms of their state of deterioration in relation to dampness problems of the building and the recent incompatible repairs.

The range of moisture content (MC) for the pillars showed much higher percentages for ground floor level. Over 90% of the ground floor pillars have MC >10% decreasing up to a 6% of the pillars in the second level. Furthermore, the dampness problems and their distribution were efficiently detected in the structure by UVM. Results indicated that the moist areas in the structure were mostly associated with ground drainage problems and the incorrect support, not to roof waterproofing or timber specie quality.

Laboratory analyses provided a reliable data for the interpretation of in situ UVM. Ultrasonic measurements were found to be sensitive to the changes in moisture content due to climatic conditions.

Juxtaposition of the MC and UVM, together with laboratory analyses were found to be useful to assess the state of timber, enhanced the accuracy and effectiveness of the survey and facilitated to build up the urgent and long-term conservation programs. 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 nondestructive technology, the expert has a real help in his surveying works.

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