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COMBINATION OF NDT AND DESTRUCTIVE TESTS FOR GRADING THE STRENGTH CLASS OF TIMBER TO REHABILITATE STRUCTURES

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ABSTRACT: Non-destructive techniques (NDT) are being implemented in the rehabilitation of the wooden structures of many old and historical buildings trying to assign the strength class of the timber. In Spain, acoustic inspection techniques are commonly used since the wave speed it can be easily predicted the modulus of elasticity. Nevertheless, the correlation with the bending strength usually is not accurate enough. By combining NDTs with destructive tests, the prediction should be significantly improved. To contrast, this hypothesis a study was carried out with the data obtained at the inspection of the timber structure in the refurbishment works done on a late 19th century Barcelona storey building. 724 beams were inspected with acoustic methods onsite and the information was complemented by testing 5 beams according to EN 408: modulus of elasticity, bending strength, density, and moisture. Finally, both sources of information were combined to develop a statistical model to assign the strength class to the beams. This study presents how the data obtained on difficult environments by NDT can be improved with destructive laboratory tests.

KEYWORDS: Non-destructive techniques, rehabilitation, strength class, timber, acoustic methods

1 INTRODUCTION

Timber was the most common material used in load-bearing structures on buildings before the massive introduction of steel and concrete in early 20th century in Catalonia. In consequence, nowadays most refurbishment works that are done on historical buildings have timber structures and old structural elements lack information about their quality or strength class. Therefore, grading all the elements is necessary to know the loadbearing capacity and minimize unexpected structural safety issues. Unfortunately, although the information obtained by the destructive tests according to EN 408 is the most accurate, destroying the elements in service to evaluate them is useless. On the other hand, Non-Destructive Testing (NDT) has a worse correlation but does not damage wood, gives valuable information and is cost-effective. A comprehensive way to evaluate an old structure is to grade visually all the elements, use acoustic waves to complement the inspection and perform destructive tests on some replaced elements. This study focuses on how to optimize the data obtained on the inspection of an existing wood structure.

2 OBJECTIVES

Improve the prediction of the load-bearing capacity of the wooden elements of an old structure in service by developing a cost-effective model based on acoustic techniques and the standardized procedure to determine the MOR, the MOE and the density.

3 METHODS

3.1 FIELDWORK

The case study is the timber structure of a five-storey building placed at 26 Trafalgar Street in Barcelona built in 1878 (Figure 1). Its constructive system was very typical in late 19th and early 20th centuries in the cities of Catalonia: masonry walls, wrought iron pillars and timber beams. The species of the beams was not determined but the gender was Pinus sp. The most common species used by that time in Barcelona was Scots pine (*Pinus sylvestris*) from the Pyrenees, but the authors also found in other contemporary buildings different common local species like Black pine (*Pinus nigra* subsp. *salzmanii*) and poplars (*Populus* sp.). In addition, also the American southern yellow pines from overseas were very common. The timber structure was in a generally good condition

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although there were elements that had issues produced by biotic agents.

The study was ordered to evaluate the safety of the new usage of the building. The inspection was done on four wood beam slabs by checking 212 beams on the ground floor, 198 on the first floor, 209 on the second floor and 105 on the third floor (Figure 2). All the 724 wood elements were inspected with a set of analysis techniques and equipment: capacitance handheld moisture meter, microsecond timer, electric drill and hand tools like hammer, awl and measuring tools. The most relevant items checked were the dimensions of the section, the span, the existence of woodworm holes and termites, the relevant splits and cracks, the biggest knots, the hardness and rot, the soundness, the moisture content and the speed of the impact waves.

Figure 1. *Façade of the building on Trafalgar Street*

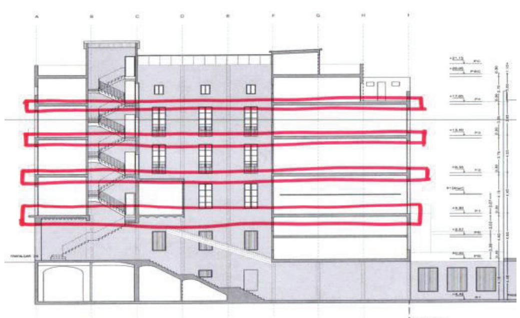

Figure 2. *Section of the building*

The microsecond timer generates impact waves with a frequency of resonance of 23 kHz and measures the time of flight between the transmitter and the receiver sensor (Figure 3). Impact waves are generated by hitting the transmitter with a hammer. Both sensors are metal nail alike transducers, they must be nailed into the wood, and the distance between them must be measured. In this case, the transducers were placed underneath the beams (Figure 4). The principle of this technique is based on the different propagation speeds of the impact waves depending on the soundness of the wood.

Figure 3. *FAKOPP Microsecond timer used in the study*

Figure 4. *Beam inspection with acoustic waves in the building*

3.2 LABORATORY TESTS

The specimens were chosen randomly between those to be removed due to the new distribution of the building. Several minor modifications and a new staircase were planned to connect the ground floor with the first floor. Five timber beams were selected for being tested at the laboratory. Three were from the new staircase on the ground floor, one was from the first floor and the other was from the second floor. The beams of the first and second floors were chosen randomly among those easier to extract. No beam was selected depending on its apparent state of conservation and all were representative of the batch. All the beams were of the same species, there were no abnormal density deviations, and the dimensions were 220×100×4000 mm. MOR, MOE, density, moisture content and stress wave tests were performed. The four-point bending test was done according to UNE EN 408:2011+A1:2012 [4] on a Hoytom bending test Machine. The test samples were symmetrically placed with a span eighteen times the depth (3960 mm) and the two load points were at six times the depth from the support point (1320 mm) (Table 2 and Figure 6).

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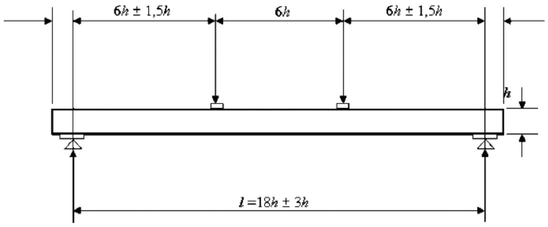

Figure 5. *Bending test geometry according to EN 408 [4]*

Figure 6. *Bending test machine at INCAFUST-CTFC*

The global static modulus of elasticity (MOE) was calculated as follows (See Equation (1):

$$MOE = \frac{3al^2 - 4a^3}{2bh^3\left(2\frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh}\right)} \quad (1)$$

Where MOE = static modulus of elasticity (N/mm^2), l = effective span distance (mm), F = load difference between 10% and 40% of maximum load (N), w = deflection difference at 10% and 40% of maximum load (mm) b = width (mm), h = height (mm), a = distance between loading point and nearest support point (mm).

The Modulus of rupture (MOR) was calculated as follows. See Equation (2) below:

$$MOR = \frac{3Fa}{bh^2} \quad (2)$$

Where MOE = static modulus of rupture (N/mm^2), F = maximum load (N), b = width (mm), h = height (mm), a = distance between loading point and nearest support point (mm).

The density was measured by drying with an oven at 103ºC up to the anhydrous state a full cross-section slice 50 mm thick cut as close as possible from the breakage point. Controlling wood moisture is necessary to correct the MOE as the stiffness varies with the water content. The five beams were checked too with the microsecond timer to correlate the stress wave speed with the MOR and the MOE. The measuring procedure was the same as the one used in the building. Finally, correlation models were developed to predict the MOE and the MOR from the dynamic modulus of elasticity (MOE_{Dyn}) (Table 4).
The dynamic modulus of elasticity (MOE_{Dyn}) was calculated by measuring the wave speed. See Equation (3) below.

$$MOE_{Dyn} = \rho \cdot v^2 \quad (3)$$

Where MOE_{Dyn} = dynamic modulus of elasticity (N/mm^2), ρ = density (kg/m^3), v = wave velocity (m/s).

Finally, the relationship between MOEDyn-MOE and MOEDyn-MOR was analysed through regression models created from the field work data and the laboratory tests results (See Table 4, Figure 9 and Figure 10). The values of the MOE the MOR and the density were corrected according to the standard EN 384 [3]. The MOE was calculated from the global MOE and adjusted by the moisture content. See equation (4) below. The density was also corrected by the moisture content to the reference conditions of 20 °C and 65% of relative humidity. The MOR was adjusted by the depth of the beam.

$$E_0 = E_0(u)\left(1 + 0{,}01\left(u - u_{ref}\right)\right) \quad (4)$$

Where E_0 = modulus of elasticity (N/mm^2), u = moisture content in the moment of the test.

4 RESULTS

Table 1, Figure 7 and Figure 8 show the wave speed on the 724 beams of the building calculated from the time of flight and the distance between transmitters. According to the Shapiro-Wilk test significant results suggest a deviation from normality (p<0,001). The coefficient of variation of the wave speed was 9.1%. Therefore, there was little variability in the data set and the arithmetic mean is a robust parameter for defining the population.

Table 1. *Beams wave speed descriptive statistics*

Descriptive Statistics	Unit	Value
Number of beams	Ut	724
Mean	m/s	5,130.348
Standard deviation	m/s	464,763
Coefficient of variation	%	9.1
Range	m/s	2,689.000
Minimum	m/s	3,543.690
25th percentile	m/s	4,823.560
50th percentile	m/s	5,176.035
75th percentile	m/s	5,483.735
Maximum	m/s	6,232.690

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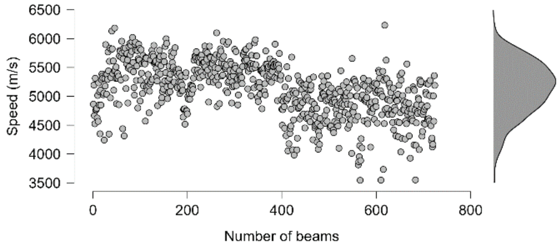

Figure 7: *Scatter plot of all the wave speed measurements (m/s) taken in the building*

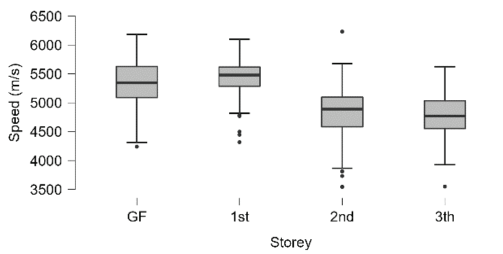

Figure 8: *Wave speed of the 724 beams divided by floors*

The wave speed of the beams split by floors showed statistical differences in accordance with the analysis of variance ($p < 0.001$) (Figure 8). The speed is slower on the upper than on the lower floors, but this difference is considered not to be intentional, and all the building was analysed as one batch.

Table 2 and Table 3 show the results of MOR, MOE, density, moisture content and wave speed of the five beams tested in the laboratory.

Table 2. *Results of the five laboratory tests*

Id. beam	MOE (N/mm²)	MOR (N/mm²)	Density (kg/m³)	%H	Wave speed (m/s)
112	11463.08	39.66	412.99	11.00	5593.22
113	12352.16	31.88	677.17	10.64	4262.10
114	11951.61	40.05	441.43	11.05	5524.74
398	12697.96	33.65	684.49	10.26	4546.62
1st floor	11736.59	33.85	404.57	11.44	5649.35

Table 3. *Descriptive statistics of the five laboratory tests*

Statistics	MOE (N/mm²)	MOR (N/mm²)	Density (kg/m³)	%H	Wave speed (m/s)
Mean	12040.28	35.82	524.13	10.88	5115.21
Deviation	490.68	3.77	143.72	0.44	658.14
CV	4.08	10.52	27.42	4.08	12.87
p_5	11517.78	32.23	406.25	10.34	4319.00

Table 4 shows the results of the models created between MOE_{Dyn}-MOE and MOE_{Dyn}-MOR with the field work data and laboratory test results.

Table 4. *Models that correlate the MOE_{Dyn} (N/mm²) with the MOR (N/mm²) and the MOE (N/mm²)*

Models developed	Correlation (R^2)
$MOE = 13767.63 - 0.15 \cdot MOE_{Dyn}$	0,76
$MOR = 24.99 + 0.00092 \cdot MOE_{Dyn}$	0,51

5 DISCUSSION

The automatic procedure to assign a strength class to a timber element is conceived to be carried out on an industrial production control where density, modulus of elasticity (MOE) and modulus of rupture (MOR) are determined with a set of advanced NDTs. Portable acoustic methods have a good theoretical correlation with the MOE but a low relationship with the MOR and the density. In fact, the correlation between the values of stiffness and strength predicted with this type of NDTs and the actual values may have a deviation between 20% and 50% [1, 2, 6-13].

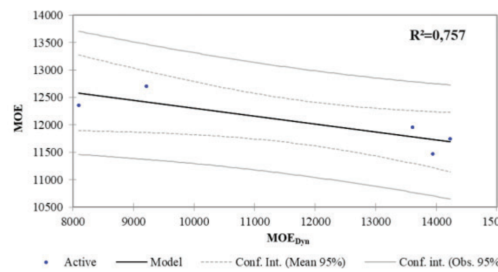

Figure 9: *Graphic of correlation between MOE_{Dyn} (N/mm²) and MOE (N/mm²)*

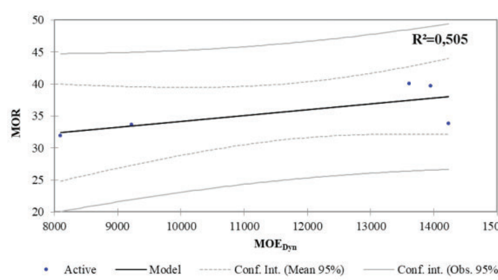

Figure 10: *Graphic of correlation between MOE_{Dyn} (N/mm²) and MOR (N/mm²)*

The correlation between the MOE_{Dyn}-MOE and the MOE_{Dyn}-MOR was below 80% (Figure 9 and Figure 10) like in the reviewed references [1, 2, 6-13].

According to the UNE EN 338:2010 [5] the 724 beams had a characteristic MOE of 11,855 N/mm², a characteristic MOR of 23 N/mm² and a density of 446 kg/m³. In consequence, the sample should be considered C27 according to the MOE, C22 for the MOR and C50 for the density. Therefore, the strength class of the 724 beams should be around C22 (Table 5).

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Table 5. *Characteristic values and strength class of the 724 beams according to the model*

Property	Characteristic Value	Strength class	Final class
Bending strength (N/mm^2)	23	C22	C22
Modulus of elasticity (N/mm^2)	11,855	C27	
Density (kg/m^3)	446	C50	

The models were specifically developed to predict the properties of the beams of the building. It must be considered that all the elements of the structure were of the same kind, and all were in a quite good condition. Therefore, in such a case the accuracy of the model should improve with an increase in the number of destructive tests.

A model with a coefficient of determination of $R^2 = 0.76$ was obtained using the MOE_{Dyn} as an independent variable and MOE as dependent variable. The results are like those discussed in other works. Arriaga *et al*. [1] found coefficients of determination for Scots pine (*Pinus sylvestris*) of 0.76 for linear regressions. Görgün and Dündar [6] obtained coefficients of determination of 0.64 for Turkish black pine (*Pinus nigra*), while Vega *et al*. [13] reported of values up to 0.68 for Sweet chestnut (*Castanea sativa*). Hermoso *et al*. [8] obtained coefficients of determination for logs of Spanish Black Pine (*Pinus nigra*) of up to 0.68. Kovryga *et al*. [10] obtained coefficients of determination of 0.65, 0.39, 0.67, 0.55 for the common ash (*Fraxinus excelsior*), the beech (*Fagus sylvatica*), the maples (*Acer spp*.), and the oaks (*Quercus spp*.) respectively. Both Hermoso *et al.* [8] and Kovryga *et al.* [10] used a Sylvatest.

The coefficients of determination of the MOR were lower and between 0.12 and 0.37. Görgün and Dündar [6] obtained a value of 0.37 for Turkish Black Pine (*Pinus nigra* var *pallasiana*), Vega *et al*. [13] found coefficients of determination of 0.11 for sweet chestnut (*Castanea sativa*) and Kovryga *et al*. [10] 0.12, 0.20, 0.16, 0.31 for the common ash (*Fraxinus excelsior*), the beech (*Fagus sylvatica*), the maples (*Acer spp.*), and the oaks (*Quercus spp.*) respectively.

In addition, the results of the study were also used to run the general model of Arriaga *et al*. [1] (Table 6) but the predicted load capacity resulted lower.

Table 6. *Strength class predicted using the model of Arriaga et al. [1]*

Method	MOR (N/mm^2)	MOE (N/mm^2)	Strength class
MOE_{Dyn} + bibliography*	23.18	9511.46	C18

* $MOE = A + B \cdot MOE_{Dyn} = 579{,}5 + 0{,}7548 \cdot MOE_{Dyn}$
* $MOR = A + B \cdot MOE_{Dyn} = -4{,}84 + 0{,}0034 \cdot MOE_{Dyn}$

6 CONCLUSIONS

Combining NDTs with destructive tests is useful to reduce the uncertainty of the prediction of the load capacity of the structural timber elements in use.

Assigning a strength class to elements that are out of the requirements of the standards is not normatively possible, but the combination of different techniques might help to make a more precise approach.

NDTs show to be a good source of information. However, proper knowledge of the material and solid experience is essential to correctly manage the data of the NDTs.

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