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Use of ultrasound as a nondestructive evaluation technique for sustainable interventions on wooden structures

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ABSTRACT

Interventions in emergency and development works normally avoid using diagnostic techniques to determine the extent of damage to wooden structures, opting instead for the large-scale replacement of elements that could otherwise be repaired or reused.

In the case detailed in this paper, the application of ultrasound non-destructive technique to assess the conservation status of the wooden frame of a building of great historical value is described. This building is known as *"El Corral del Conde"* and is located in the city of Seville (Spain). The aim is to limit the scope of the intervention with an approach based on the principle of sustainable intervention, which minimizes the replacement of materials that could be recovered and thus reducing CO_2 emissions. The results show that using nondestructive techniques is possible to reduce the total volume of the intervention minimizing the energy consumption and CO_2 emissions by 85 percent.

1. Introduction

Interventions performed on existing structures require prior diagnosis to evaluate the structural behavior and condition of the structure. The information derived from this analysis determines the type of intervention to be applied in each case [1]. This information is crucial to ensure a reliable assessment of the safety and serviceability level of the structure. Only then can efficient repair or strengthening solutions be proposed.

In the case of wooden frameworks, the evaluation of their structural behavior depends on proper access in order to assess *in situ* the physical and mechanical properties of the constituent elements, among other factors [2]. A complete assessment requires the use of special tools and methods to obtain objective knowledge of the material and the level of deterioration [3–5].

The effectiveness and reliability of nondestructive inspection techniques, including ultrasound methods, involve prior laboratory testing to reveal the physical and mechanical properties of the material, by means of correlations with destructive tests [6,7]. Then, the application of these tools in the diagnosis process has to be carried out by specialists familiar with the techniques and capable of interpreting the results of each inspection.

Ignorance of or a failure to carry out these inspection techniques means that an accurate diagnosis cannot be made, which could lead to large-scale replacement of the damaged sections to ensure the safety of the structure. This type of intervention, which is economically and environmentally unsustainable, means discarding material that could otherwise be suitable for structural use.

Besides sustainability, in recent years, issues such as the preservation of our architectural heritage have boosted support for the development of procedures that can guarantee the integrity of existing historic building and wooden structures, generating a great interest in the use of non-destructive diagnostic techniques [8,9].

Sustainability in current constructive processes examines, among other aspects, energy consumption and CO_2 emissions associated to the manufacture of the construction materials and the construction process itself. This is called embodied energy in the building. The problem with embodied energy is that today's most widely used energy sources in the productive processes are non-renewable, and these also produce large amounts of greenhouse gas emissions, including CO_2. One of the goals of sustainable development is to replace non-renewable energy sources and fossil fuels with clean renewable sources of energy, cut CO_2 emissions and reduce the amount of energy embodied in the products we consume.

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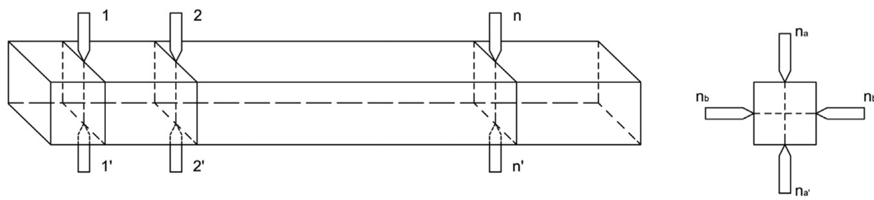

Fig. 1. Measurement of ultrasound velocity for lab samples.

This paper presents a proposal for a sustainable intervention in a building with a great historical value "*El Corral del Conde*", in Seville. This proposal is derived from a previous inspection process by non-destructive techniques of ultrasound, and analyzes CO_2 emissions and energy consumption. This proposal is opposed to the actual intervention based on the large-scale replacement of elements.

2. Ultrasound as a nondestructive evaluation technique

Ultrasonics is a non-destructive test (NDT) widely applied in the analysis of concrete, stone and wooden elements [10,11]. It measures the acoustic properties of materials by recording the propagation velocity of the stress waves in an elastic medium. Then propagation velocity is related to the rigidity and density of the medium. This measurement informs of the compactness of the material and detects any irregularities.

Ultrasound has been applied to wood since the 1950s. Since then, two lines of research in this field have been developed:

1. Sound wood: Assessment of the strength of new wood in sawmills, based on longitudinal ultrasound transmission speeds [12,13]. The propagation velocity of the ultrasonic waves that move longitudinally across the grain enables to obtain the dynamic elasticity modulus value by means of the following equation:

$$E_d = V_L^2 \cdot d \quad \left(\text{N/mm}^2\right) \tag{1}$$

E_d Dynamic elasticity modulus (N/mm^2)
V_L Ultrasonic velocity parallel to the grain (m/s)
d Wood density (Kg/m^3)

According to the literature, the modulus obtained by this equation is, on the average, 5% higher than that which might result from by the bending test [14].

2. Decayed wood: Quantifying the state of decay of wooden structures under restoration, based on perpendicular to the grain ultrasound transmission speeds [15,16]. The ultrasonic propagation velocity value measured perpendicularly to the grain of the wood allows to locate any internal losses in material density. The presence of cavities caused by deterioration manifests as an alteration in the ultrasonic propagation velocity values. Consequently, the results provide information on density loss in a section of the element.

How to predict density loss and residual strength in a wood element is one of the aims regarding the application of non-destructive techniques in timber member in-service. In this line of research the authors have developed a specific methodology based on laboratory tests to determine the density (in healthy wood) or density loss (if decayed) and the residual resistance in a wood element in-service.

The proposed method is based on measurements of ultrasonic propagation velocities perpendicular to the grain in each timber member examined (Fig. 1). The choice of the test sections is determined beforehand after a visual inspection. The measurements obtained are related to the regression curves obtained previously in laboratory.

In this paper, two relationships determined for deteriorated wood are shown. These correlations can estimate the density loss (Δd) of a decayed wooden element [Eq. (2)] and its compressive strength parallel to the grain (f_c) [Eq. (3)] via the ultrasonic velocity perpendicular to the grain.

$$\Delta d = 53.257 - 0.0396\, V_n (\%) \quad \left(R^2 = 0.81\right) \tag{2}$$

Δd Density loss (%)
V_n Ultrasonic velocity perpendicular to the grain (m/s)

$$f_c = -1.1069\Delta d + 50,686 \left(\text{N/mm}^2\right) \quad \left(R^2 = 0.73\right) \tag{3}$$

Δd Density loss (%)
f_c Compressive strength parallel to the grain (N/mm^2)

These correlations were obtained from 48 small samples of Scots Pine (*Pinus Sylvestris*) with a size of $20 \times 20 \times 60$ mm^3. Wood used in these samples was extracted from rotten wooden beams found in ancient structures. Each beam was divided into several sections. Then, both sound and damaged samples were taken from each section. The samples were conditioned to a moisture content of approximately 12%. Density loss was measured by comparison between the mass of sound and damaged wood.

Given the influence of the moisture content on the ultrasonic transmission velocity perpendicular to the grain (V_n) [17], another expression was obtained in order to refer all measurements to the same moisture content (12%).

$$V_{n12} = 15.89(H_1 - 12) + V_{n1}(\text{m/s}) \quad \left(R^2 = 0.93\right) \tag{4}$$

V_{n12} Ultrasonic velocity perpendicular to the grain (m/s) with a moisture content of 12%
V_{n1} Ultrasonic velocity perpendicular to the grain (m/s) with a H_1 moisture content (%)
H_1 Moisture content (%) different to 12%

This correlation was obtained from 10 small samples free of defects of Scots Pine (*Pinus Sylvestris*) and with a size of $20 \times 20 \times 300$ mm^3.

Moisture content also affects the density value, and in this case the density value is corrected according to the formulation in the UNE-EN 384 standard [18] [Eq. (5)]: