Case Studies in Construction Materials 19 (2023) e02311

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Diagnosis and assessment of a historic timber structure in La Casa del Corregidor, using non-destructive techniques

Gamaliel López [a], Patricia Vallelado-Cordobés [a,*], José Luis Gómez-Royuela [b], Luis-Alfonso Basterra [a]

[a] *Departamento de Construcciones Arquitectónicas, ETS Arquitectura, Universidad de Valladolid, Avda. Salamanca 18, Valladolid, Spain*
[b] *Departamento de Estructuras, ETS Arquitectura, Universidad Politécnica de Madrid, Av. de Juan de Herrera, 4, Madrid 28040, Spain*

ARTICLE INFO

Keywords:
Assessment
Timber structures
Methodology
Non-destructive methods
Strength grading
Rehabilitation

ABSTRACT

This paper presents the assessment of the timber structure of “La Casa del Corregidor” building, a singular historic building in Cuenca (World Heritage City). The building is scheduled for restoration in the near future. The study made use of both non-destructive (NDT) and semi-destructive (SDT) techniques.

A thorough experimental campaign and inspection were conducted on all the old wood elements across the eight floors of the building. More than 1200 elements of *Pinus sylvestris L.* wood were inspected. The data collected in this campaign allowed a mechanical evaluation of the timber elements.

The following NDT and SDT were used: visual inspection, microphotography, moisture meter, stress-wave measurements, and resistance drilling. These techniques made facilitated the identification of the wood species, detection of natural defects and decayed areas, and estimation of the physical and mechanical properties of the timber elements. The experimental results were statistically analysed using a multidisciplinary approach to determine the scope of the intervention on the structure to meet the new use and its structural requirements. The final report produced at the end of the inspection was made of colour plans describing the singularities, natural defects, timber decays and damages of each single member.

The results obtained will orient the building’s conservation work. These findings support a minimal intervention, since more than 95 % of the structural elements were found to be in good condition.

1. Introduction

The resurgence of timber as a structural material can be attributed to two main factors. Firstly, there is a growing emphasis on the preservation and restoration of historic buildings, which often feature ancient timber structures. Secondly, timber possesses unique characteristics that make it a sustainable and environmentally friendly material. Moreover, knowledge about material has been enhanced and there are several recent publications of international standards.

Ancient timber structures are commonly found in architectural heritage buildings. They are an important part of our culture and testify the primary way of conceiving structures [1]. In recent years, the restoration of these historic building has focused not only on

* Corresponding author.
E-mail address: pvallelado@uva.es (P. Vallelado-Cordobés).

https://doi.org/10.1016/j.cscm.2023.e02311
Received 26 April 2023; Received in revised form 12 July 2023; Accepted 13 July 2023
Available online 17 July 2023

covering the mechanical lacks of the structure, but also on achieving an energy behaviour enhancement [2]. Some of the latest technological advances, as Building Information Modelling (BIM), have begun to be applied on these buildings in order to get a global view of various solutions [3].

The assessment of structural timber, particularly ancient timber, and the prediction of its behaviour always supposes a challenge. Wood is an organic and anisotropic material with high variability of its physical and mechanical properties. Knowing these properties is essential to assess the structural safety and stablish the scope of the intervention. Defining the nature and the extent of the scope of works is also crucial in estimating the cost of timber restoration [4].

While visual inspection remains a fundamental step in assessing timber condition, instrumental methods for inspection have emerged over the past few decades [5]. Depending on the damage these methods produce to the timber members analysed, they are denominated non-destructive (NDT), semi non-destructive (SDT) or destructive tests (DT). They usually give some information regarding the characterization of timber correlating the parameter measured with some of its mechanical properties. The attention in these techniques is quickly growing, and their use is becoming more widespread.

The aim of the present work is to apply an assessment methodology to the specific case of the “Casa del Corregidor” in Cuenca. The primary goal is to collect the necessary data to assess the structural safety for keeping the design of the rehabilitation works to a minimum, in accordance with International Council on Monuments and Sites (ICOMOS) recommendations [6]. This work was the basis for the whole restoration project.

2. The building

The ‘Casa del Corregidor’ is an historic palace that served as the residence of the Corregidor, a high official ranked of the Spanish empire. The building is located on the site of a former medieval prison. Its current configuration is the result of an 18th-century reform carried out on a previous structure from the mid-16th century. The total built area is about 2210 square meters.

The section reflects a marked overlap in height resulting from the special topography of the San Martín district, and the use of the building [Fig. 1]. It is divided into two distinct sections: an upper residential part for the Corregidor and a lower section accessible from the slope of Santa Catalina. The lower part, which encompasses the first five floors, is not visible from the main entrance but can be observed from the canyon of the Huecar River. This section constitutes the largest portion of the building [Fig. 2].

The facade overlooking Alfonso VIII Street is austere, with a series of balconies on the main floor. It is emphasized by an asymmetrical shield on the access axis. The openings of the different floors and the corners are framed in stone, and adorned with delicately textured coatings, simulating cut stone masonry. The interior is accessed is through a hallway that leads to two sets of stairs, one descending to the prison’s basement and the other ascending to the residential first floor [Fig. 2]. From the rear, the building entity and its imposing volumetry can be clearly seen. It shows a stone masonry wall partially plastered. Several of the openings and corners are also framed with better quality masonry pieces [Fig. 2].

The roofs are covered with curved ceramic tiles, seated on wooden structures, partially replaced in the palatial area by a recent system of metal trusses. Roofs usually requires more maintenance and restoration due to exposure to weather [4]. The roofs are finished off frontally and laterally with relatively prominent eaves of corbels.

The owner intends to rehabilitate the building to be used as a town museum, municipal archive, and office spaces.

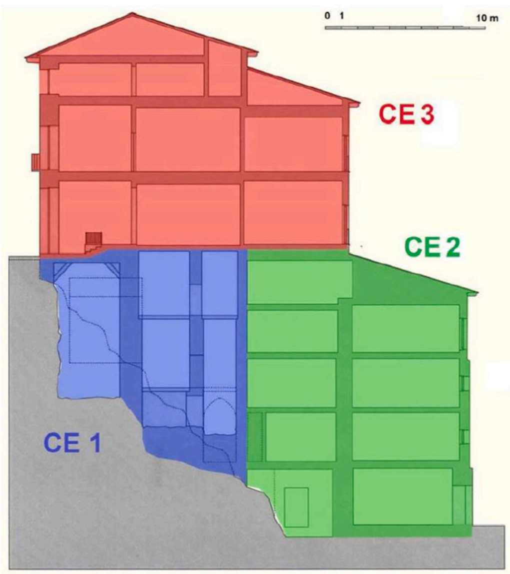

Fig. 1. Section marking the three constructive stages.

Fig. 2. Facade to Alfonso VIII Street (left) and rear facade (right).

2.1. The timber structure

The building has been out of use for several years, resulting into a constructive and functional degradation. Without prompt rehabilitation, this degradation poses a risk of irreversibility. Three previous restoration projects have been found, 1997, 2006 and 2009, but none of them were carried out, except for the partial replacement of the roof.

Excluding part of the roof structure of the residential palatial area, the rest of the structural systems studied correspond to their original configuration. The vertical systems are stone masonry walls, sometimes starting from baseboards of finely worked ashlar pieces. In addition, there are some partition walls made with wooden frames filled with adobe or stone masonry. There are also some vertical wood supports lying on a stone piece to isolate them from the humidity of the ground. The foundations have only been locally visualized, they are made of stone masonry supported on rock, a common foundation in this town.

Two traditional typologies of one-way slabs can be found, each displaying considerable variability in the cross-sections of the joists.

Fig. 3. Floor type 1 (left) and floor type 2 (right).

In the first typology, the space between joists is around twice their width, and it is filled of masonry materials coated with plaster on the bottom. In the second typology, the space between joists is variable and the wooden board is nailed directly to the joist upper side width [Fig. 3].

3. Methodology and assessment

The assessment of timber structures includes several fields of knowledge, such as art history, restoration, architecture, and structural and forestry engineering. In addition, it often depends on the experience and expertise of the involved professionals. To minimize the subjectivity, and facilitate decision-making, some methods have been developed to provide with objective data.

Although few guidelines have been published [7,8], three common steps can usually be found in many assessment methodologies: preliminary assessment; structural analysis and detailed assessment; and assessment results and future actions [9]. In general, the evaluation of timber structures and the study of them as a whole is increasingly recognised as requiring a holistic approach [8–10].

Strength grading of timber is a crucial aspect of the assessment procedure. The initial step is visual grading, which is the most commonly used method. It involves the observation of the natural defects, the damage and deterioration, and the member's size. In addition to visual classification, other instrumental methods are used (NDT and SDT). These methods usually correlate a non-destructive parameter, such as a stress-wave velocity or resistance drilling, with a physical property such as strength or modulus of elasticity [11]. A combination of different methods has been pointed out as the best way to predict the structural behaviour and improve the assessment [11–14].

Based on this background, and on some previous structural timber assessments carried out by our research group [15], a holistic methodology combining visual, and some instrumental methods is proposed and tested. The procedure steps applied on the timber structure assessment of the 'Casa del Corregidor' are as follows [Fig. 4]:

3.1. Preliminary research

A preliminary visual survey was carried out after collecting and analysing the information related with the building (plans, texts,

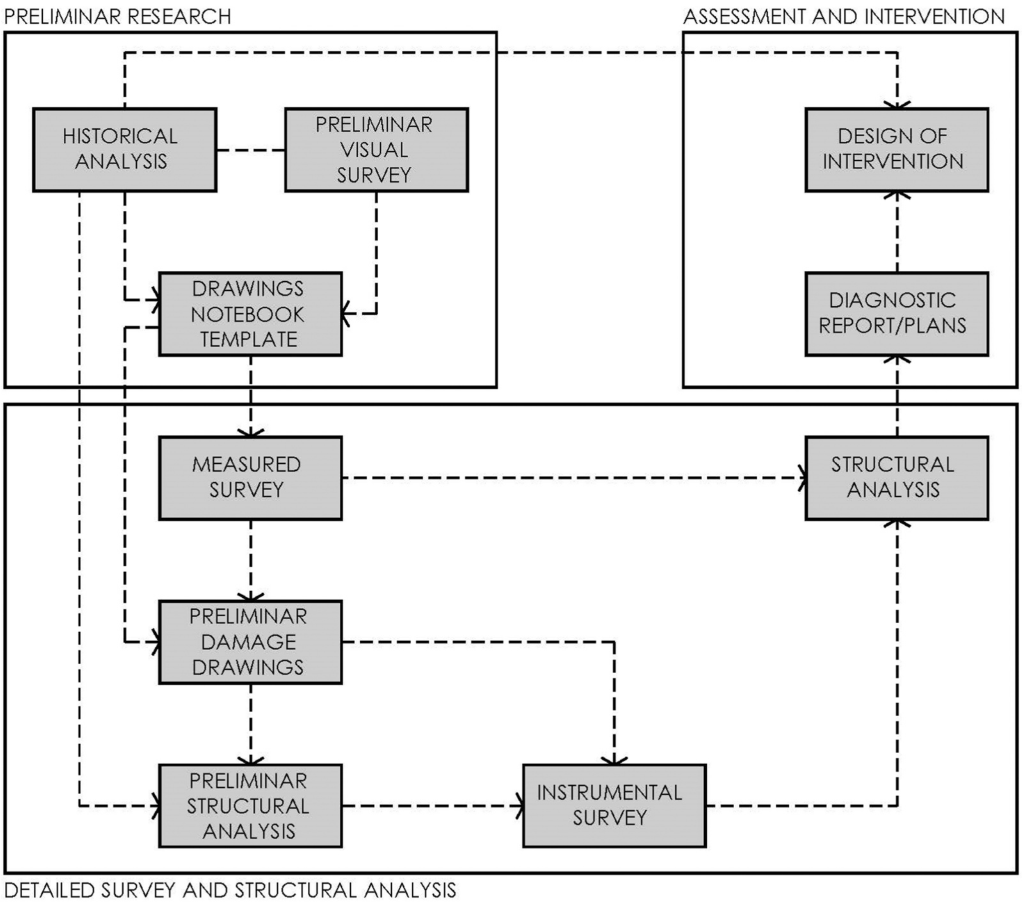

Fig. 4. Assessment methodology (by Authors).

photos) and checking all use changes and interventions suffered during its lifetime. All floors were superficially inspected checking global geometry and structural plans accuracy. In order to facilitate the process, beam fills were removed to expose all sides of the joists and beams. Finally, a survey notebook numbering all the rooms in each floor, was prepared.

3.2. Detailed survey and structural analysis

The visual inspection is the most important step on every structural assessment methodology [11]. Whenever possible, all the timber structure must be inspected [8]. A complete knowledge requires extending the inspection to more than 80 % of the structure [10]. In this case, all timber were inspected floor by floor and room by room, encompassing a total of 1218 elements, distributed as follows:

Pillars	4
Beams	56
Joist	1158
Total	1218

Each room was drawn in section to check the sections geometry and the regularity of the space between joists as follows [Fig. 5]:

General photographs of each room were taken, while detailed pictures were captured of beams or joints when necessary. The point of view of each photo is indicated on the plans. An accurate geometric evaluation of both structure and cross sections of all elements were defined and represented on plans. The representation work was made according to a system implemented by our research team and standardized by UNE 41808 [16], resulting as follows [Fig. 6]:

Overall, the condition of the timber structure was good, particularly for the upper floors located above the access road. However, the lower level shows worse condition, especially in the rooms adjacent to and below to the main access, as they are in contact with the ground rock on which the city was built.

The cross-section of all elements was measured, revealing slightly larger than the expected. Most of the beams and joists have a rectangular geometry, although some of them show irregularities due to the wanes. A few beams have an inverted T-section, eliminating the need for side timber strips to support the beam infills. Additionally, round section beams have been observed occasionally.

All natural defects were inspected and measured, paying particular attention to knots and slope of grain. In old timber, with large cross sections, bigger than commercial sizes, the structural behaviour is mainly affected by knots and slope of grain [18,19]. Some biological damage was found, essentially larval-cycle insects and some fungi, although no termite infestations were found. These insect attacks are mostly superficial, old and inactive. The statistical distribution of natural defects, decays and damages detected on timber members is as follows:

Knots	52·22 %
Resin bags	2·55 %
Wanes	37·93 %
Checks	30·87 %
Warps	2·46 %
Singular section	4·43 %
Round sections	1·31 %
Larval cycle insects	23·56 %
Fungi	3·45 %
Moisture	2·30 %

Once detailed visual inspection was completed, a visual strength grading was applied according to the European and Spanish national standards. Grading criteria depend on the structural quality and wood species. The standard UNE 56544 [20] evaluates

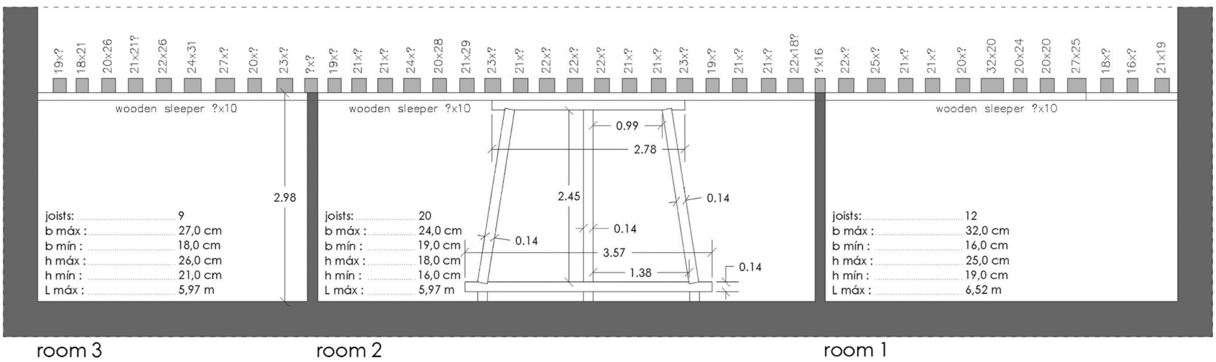

Fig. 5. Room section.

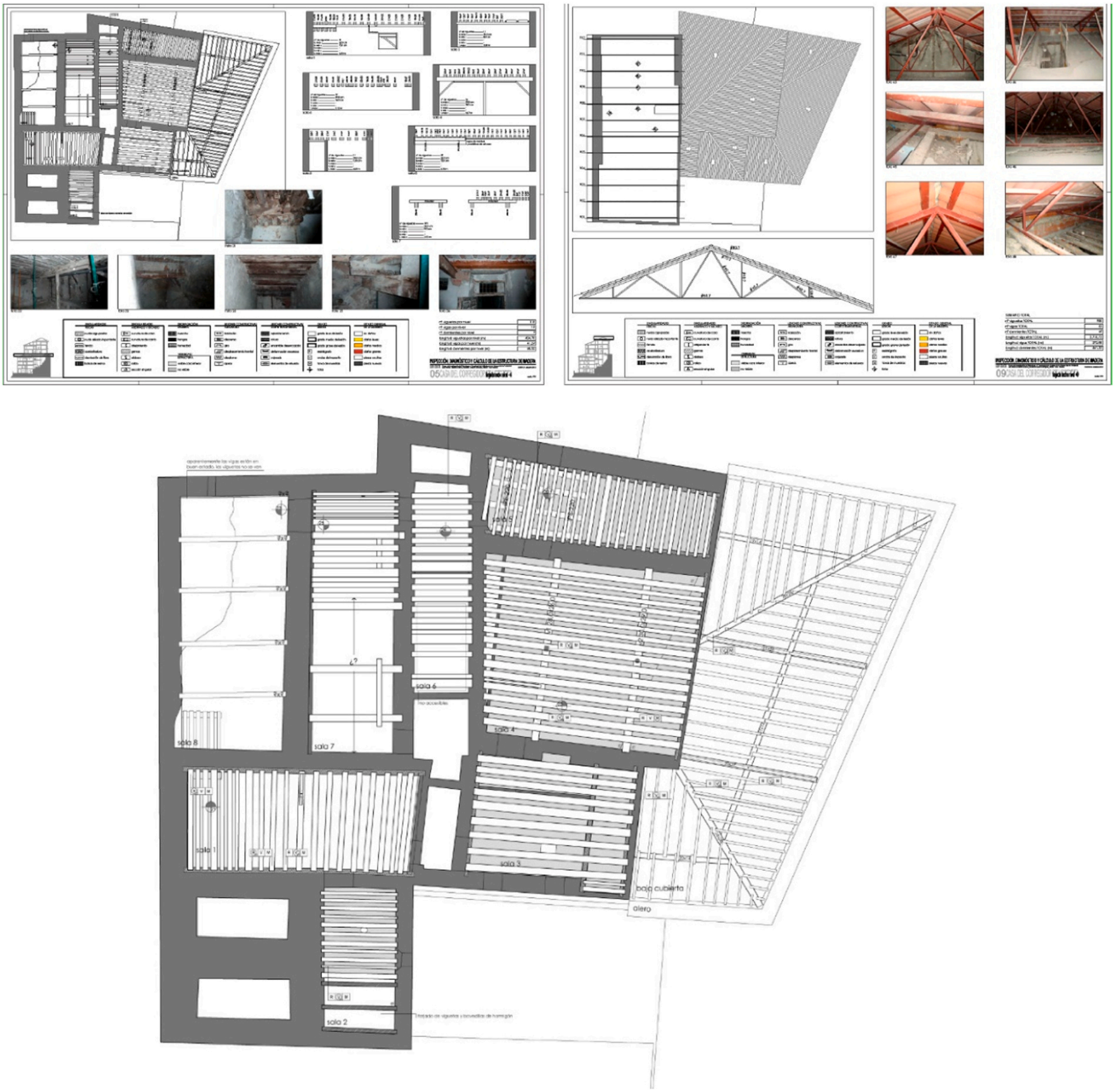

Fig. 6. Some examples of structure descriptive plans. All plans are available for consultation in hq in [17].

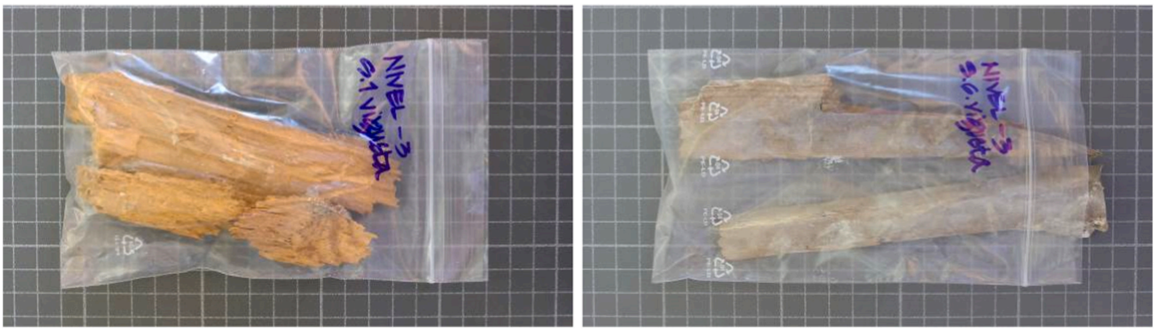

Fig. 7. Wood samples available for consultation in [17].

singularities and geometrical features, such as knots, resin bags, checks, slope of grain, growth rings, wanes and warps, and biological decays, such as fungi and larval cycle insects. One of the grades applies specifically to large-cross sections, usual in ancient timber elements. Standard EN 1912 [21], assigns strength class according to the visual strength grades, species and sources of timber. The result was checked against the instrumental methods.

After the detailed visual inspection, microphotography, micro second timer by Fakopp® and Resistograph® were used to evaluate both the biological condition and the mechanical properties of the timber. Moisture content and density were also quantified.

3.3. Microphotography

A visual macroscopic analysis indicates that the wood used in the structure belong to the general group of softwood, specifically to the genus *Pinus*. However, in order to get a positive identification of the species, nineteen material samples of 150 × 150 × 150 mm were obtained from different areas of the structure inspected [Fig. 7].

To identify the wood samples, the existence of the following elements was appraised [Fig. 8]:

a) Homogeneous structure and non-existence of vessels.
b) Longitudinal resiniferous canals located at the end of the growth ring.
c) Inner walls of the radial tracheids with pronounced and abundant teeth.
d) Crossing-field pits of either pinoide I or window type; dentate radial tracheids.
e) Uniserial woody radii; some of which are fusiform-like with radial resin canals.

The observed characters lead to the possibility, with high probability, that the analysed samples belong to the species *Pinus sylvestris L.*, commercially known as Scots pine.

3.4. Moisture content

Density and moisture content (MC) are historically the first physical properties related with the mechanical ones. The MC influence is important for grading and for NDT and SDT results calibration [14]. All wood properties are affected by MC. High values decrease strength and stiffness properties and, besides, increase risk of biological attacks. The MC constantly seeks equilibrium with the environmental conditions. Thus, MC changes over time depending on the environmental changes, and varies even along the same structural member.

In the present assessment, MC was measured by means of electrical methods, specifically with a moisture meter. This method is based on the relationship between MC and the direct current conductance of wood [22]. MC was measured between two or five pieces in each room, depending on the size of this room, resulting in a total of 171 measurements. The determination was based on three readings in three different areas of each piece using a xylohygrometer Surveymaster®. All members inspected present a value in the range 8.7–12.8 %, except some pieces located in the lower levels and closed to the ground rock. This unsignificant variations were expected, as the building has been unused and permanently ventilated.

3.5. Density evaluation

The assessment of timber structures relies to a large extent on the knowledge of the density, as it offers good information about the quality and preservation of the pieces. The density was determined on samples obtained from the building with a cross-section of 20–25 mm and a fiber length of 100 ± 5 mm. After drying the samples, the mass and volume in anhydrous state are determined [23].

A total of 28 samples were obtained and tested. One of them was rejected because it showed signs of biodeterioration. The values

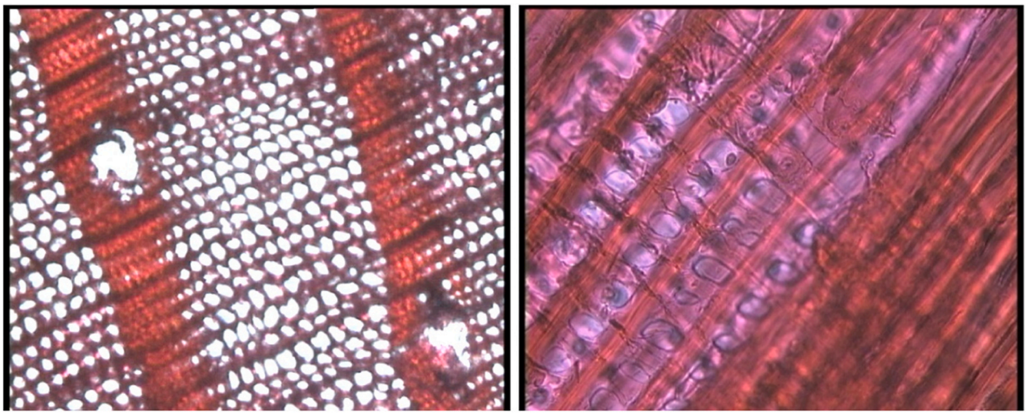

Fig. 8. Transversal and radial cut.

measured were between 408.40 kg/m^3 and 606.70 kg/m^3 [Table 1].

3.6. Impact-wave. Micro second timer by Fakopp® (MST)

Measurement of ultrasonic velocity through wood is one of the oldest, most developed and still most widely used technique on timber structural assessment [24]. This method determines the speed of ultrasonic wave propagation through the wood, usually by measuring the time-of-flight of the impact waves. The wave velocity is affected, among others, by the presence of knots, resin bags and any decay or discontinuities in the wood internal structure. It is also affected by the angle of measure used in relation with the grain direction [25].

This technique is used both to detect internal cracks, knots and decay and to predict the dynamic Modulus of Elasticity (MOE_d) [26]. Knowing density, timber geometry and length between sensors MOE_d can be obtained according to:

$$MOE_d = V^2 \rho \tag{ec.1}$$

where MOE_d is the dynamic MOE, V wave propagation velocity and ρ mass density.

This method is highly subjective, but many NDT testing methods have analyzed the propagation of sound waves to provide quantitative measures based on empirical relationships [24]. Extensive research about the relation between MOE and MOE_d has been done in different species reporting correlation coefficients between 0.58 and 0.97 [11,26]. Pošta et al. [27] obtain a correlation coefficient $R^2 = 0.95$ using MST device testing *Picea abies*, Van Duong [28] found a high coefficient 0.92 testing *Melia azedarach*, Wang et al. [29] studied four species of conifers and reported an interval of correlation 0.84–0.91. Finally, Arriaga et al. [30] studying *Pinus radiata*, *Pinus sylvestris, Pinus pinaster* and *Pinus nigra* obtain a 0.81 factor. Arriaga's model considers the type of sensor used and its placement. This is the model followed since the species of wood used in the structure of 'Casa del Corregidor' and the type of sensor coincides with the study.

Two steps were taken to obtain the MOE. First, a correction was applied to the wave propagation velocity: MST was placed face to face, measuring perpendicular to the grain direction. Balmori et al. [25] proposed the following model:

$$V_{0,eq} = V_{90} + 348{,}938\ \sqrt{\alpha} \tag{ec.2}$$

where $V_{0,eq}$ is the equivalent wave propagation velocity measured parallel to the grain, V_{90} is the wave propagation velocity obtained and α is the angle of measurement (90° in this case).

Table 1
Density values.

Density values for samples of the structure				
#	Level	Room	Element	Density (kg/m^3)
1	0	1	Beam V2	526.70
2	0	1	Joist	606.70
3	0	2	Beam V1	546.10
4	0	2	Joist	508.40
5	1	1	Joist	558.00
6	1	2	Joist	521.55
7	1	3	Joist	515.95
8	1	6	Joist	591.50
9	2	1	Joist	468.90
10	2	2	Joist	487.25
11	2	4	Joist	461.45
12	2	5–6	Common beam	424.80
13	3	2	Joist	456.90
14	3	4–5	Common beam	441.90
15	3	7	Joist	561.25
16	4	1	Joist	555.55
17	4	3	Joist	600.00
18	4	7	Joist	586.20
19	5	1–3	Common beam	578.90
20	5	2	Joist	572.35
21	5	4	Joist	488.55
22	5	12	Joist	566.75
23	6	4	Pillar	449.60
24	6	6	Beam	589.40
25	6	8	Joist	514.30
26	7	3	Joist	593.10
27	7	2	Joist	408.40
28	7	12	Deck file	479.30
			Average	505.51
			CoV	12 %
			5 % Percentile	415.78

Secondly, Arriaga's model [30] was followed to relate the MOE and MOE_d. This study coincides with the species of wood used in the structure of 'Casa del Corregidor' and the type of sensor used. After applying the ec.2 correction, end-to-end measured were considered.

$$MOE = -1384 + 0{,}9131\ MOE_d \tag{ec.3}$$

Taking into account the characteristic density obtained by the density evaluation, [31]he tests results of the MST are shown in Table 2.

The average speed (1795 m/s) is higher than the reference speed listed by the manufacturer of the equipment for this species (1470 m/s), reflecting the good state of preservation of the wood pieces.[32].

Table 2
MST results.

Impact-wave. Micro second timer by Fakopp®								
		L [cm]	Time [μs]	v_{90} (m/s)	$v_{0,eq}$ [a] (m/s)	MOE_d [b] (MPa)	MOE [c] (MPa)	%
	Level 0							
FT01	Room 02	18,0	109	1.651	4.962	10.236	7.962	78 %
FT02	Room 07	21,0	123	1.707	5.018	10.468	8.174	78 %
FT03	Room 04	18,7	98	1.908	5.218	11.323	8.955	79 %
FT04	Room 12	20,7	110	1.882	5.192	11.209	8.851	79 %
FT05	Room 11	19,0	91	2.088	5.398	12.116	9.679	80 %
	Level 1							
FT06	Room 10	20,7	122	1.697	5.007	10.424	8.134	78 %
FT07	Room 01	20,3	115	1.765	5.076	10.711	8.396	78 %
FT08	Room 05	19,8	114	1.737	5.047	10.592	8.287	78 %
FT09	Room 08	11,7	73	1.603	4.913	10.036	7.780	78 %
FT10	Room 09	21,5	120	1.792	5.102	10.823	8.498	79 %
	Level 2							
FT11	Room 02	20,7	111	1.865	5.175	11.136	8.784	79 %
FT12	Room 02	20,9	126	1.659	4.969	10.266	7.990	78 %
FT13	Room 01	20,0	99	2.020	5.331	11.814	9.404	80 %
FT14	BC	19,0	105	1.810	5.120	10.899	8.568	79 %
FT15	BC	18,4	106	1.736	5.046	10.587	8.283	78 %
	Level 3							
FT16	BC	23,0	134	1.716	5.027	10.506	8.209	78 %
FT17	BC	20,0	99	2.020	5.331	11.814	9.404	80 %
FT18	Room 04	27,3	130	2.100	5.410	12.171	9.729	80 %
FT19	Room 04	21,3	106	2.009	5.320	11.766	9.360	80 %
FT20	Room 05	24,5	126	1.944	5.255	11.481	9.099	79 %
FT21	Room 06	21,0	124	1.694	5.004	10.411	8.122	78 %
	Level 4							
FT22	Room 03	18,2	96	1.896	5.206	11.269	8.906	79 %
FT23	Room 03	18,6	102	1.824	5.134	10.958	8.622	79 %
FT24	Room 07	18,3	104	1.760	5.070	10.687	8.375	78 %
FT25	Room 01	20,5	127	1.614	4.924	10.083	7.823	78 %
	Level 5							
FT26	Room 01	18,9	99	1.909	5.219	11.327	8.958	79 %
FT27	Room 01	26,2	135	1.941	5.251	11.465	9.084	79 %
FT28	Room 04	26,0	138	1.884	5.194	11.218	8.860	79 %
	Level 6							
FT29	Room 02	22,9	158	1.449	4.760	9.419	7.217	77 %
FT30	Room 03	21,0	118	1.780	5.090	10.772	8.452	78 %
FT31	Room 01	20,3	118	1.720	5.031	10.522	8.224	78 %
FT32	Room 06	29,2	220	1.327	4.638	8.942	6.781	76 %
	Level 7							
FT33	Room 01	33,6	180	1.867	5.177	11.143	8.791	79 %
FT34	Room 01	21,0	114	1.842	5.152	11.038	8.695	79 %
FT35	Room 01	31,6	218	1.450	4.760	9.420	7.217	77 %
FT36	Room 01	30,0	160	1.875	5.185	11.179	8.824	79 %
FT37	Room 01	29,0	145	2.000	5.310	11.725	9.322	80 %
FT38	Room 02	27,3	150	1.820	5.130	10.943	8.608	79 %
FT39	Room 02	23,0	140	1.643	4.953	10.201	7.930	78 %
	Average	22,1	125	1.795	5.105	10.849	8.522	79 %
	5 % Percentile					9.419	7.217	

[a] $v_{0,eq} = v_{90} + 348{,}938^{*}\sqrt{\alpha}$
[b] $MOE = -1384 + 0{,}9131^{*}MOE_d$
[c] $MOE_d = \rho_{med}\ ^{*}v^2$

3.7. Resistograph®

This technique records the energy consumed by a calibrated steel needle drilling the wood with constant speed and rotation. This energy is directly related with the wood resistance to be penetrated. All energy or resistance variations are printed in a graphic, named resistogram. This technique may be used not only to locate hidden timbers, detect internal discontinuities or assess the extent of decay or damage, but also to predict mechanical properties of wood [11,12,26,33,34]. Average values of Resistance Measure (RM) have been related to density with correlation coefficients between 0.36 and 0.88, to MOE with correlations coefficients between 0.52 and 0.67, to compressive strength along and perpendicular to the grain with correlations coefficients between 0.47 and 0.78, and to hardness with correlations coefficients between 0.35 and 0.65 [35–38].

This technique is used to detect internal deterioration and density loss in timber members. It is also used to complete the information gathered by the other instrumental tests and visual inspection. 25 tests were performed, carefully selected on the basis of the detailed visual inspection. Spots tested were close to the embedment of the joists in the wall, and close to joists with some of their section face hidden. All 25 test are available for consultation in [17].

3.8. Structural analysis

The building stability is ensured by the thick stone masonry walls in two orthogonal directions and the absence of large openings.

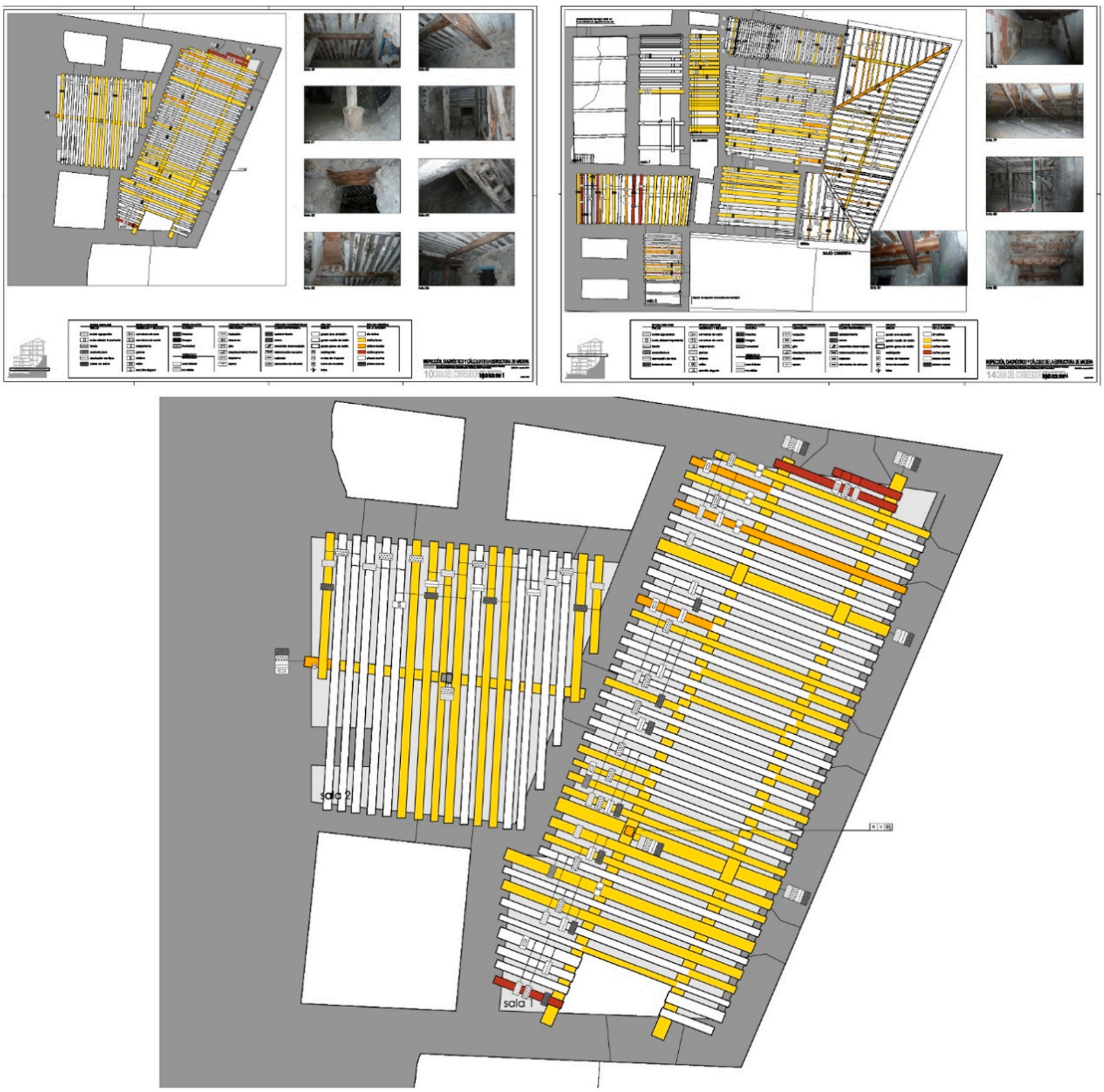

Fig. 9. Examples of diagnostic plans. All plans are available for consultation in hq in [17].

For the structural timber elements, boundary conditions must be determined first. Around 95 % of the timber structure analysed are pinned-pinned joists, forming one-way floors, traditional solution in heritage buildings. The rest of the structure is composed of 56 beams, most of them also with pinned support type. Only 3 continuous beams with two spans have been found. Four wooden pillars complete the whole timber structure. Carpentry joints have not been detected.

The longest joist of every single room in all the levels, and all the most loaded beams were analysed according to the theory of strength of materials. Stress levels and displacements were determined applying the classical pinned-pinned formulas, the instrumental values obtained, the cross sections measured and the expected load for the new use. According to Eurocode 5, load duration classes and service classes were also taken into account. Almost all the structure has been service class 2: "*moisture content in the materials corresponding to a temperature of 20 °C and the relative humidity of the surrounding air only exceeding 85 % for a few weeks per year* " [39].

The stress levels resulted lower than the joists and beams load-bearing capacity. The displacements were also smaller than those allowed by the Spanish standard [40].

3.9. Graphic representation

All visual and instrumental data collected were mapped on specific diagnostic plans, one per level [Fig. 9]. These scaled drawings comprised section dimensions, singularities, natural defects, timber failures and decays, construction and mechanical damages, concealed areas, as well as instrumental test and photos location. On these plans damage intensity was marked with a colour code and thickened boxes in accordance with the standard UNE 41808 [16].

These detailed maps provide local and global information about state of preservation. Deteriorated areas can be graphically shown, helping to find the causes of damage or pathologies if they exist. In addition, the use of colour facilitates taking a decision for the design of the intervention if need it.

All diagnostic and survey plans are available for consultation in [17].

4. Results and discussion

The whole structure was inspected; every single timber member was checked, and all the cross sections were measured. Significant variation was observed, not only in geometric section properties, but also in the spacing between joists. Approximately 40 % of the pieces exhibited wanes and checks, although there was no significant reduction in cross sections. Knots were present in around half of the elements, but few exceeded the limits established by UNE 56544 [20].

Larval cycle insect attacks were found in a slightly over 20 % of the elements. However, all of this damage was superficial, old and inactive. The majority was concentrated in the lower levels, specifically in the rooms in contact with the ground rock. This decay pattern was expected, as basement floors typically have higher moisture levels.

Using UNE 56544 [20], a visual MEG quality could be assigned to healthy wood pieces. Consequently, for *Pinus sylvestris L*. wood, determined by microphotography, and according to EN 1912 [21], an equivalent C22 strength class could be identified.

An average value for MC was quantified between 8.7 % and 12.8 %, with unsignificant variation along the whole structure, probably because the building was abandoned and ventilated. Only some elements located in lower rooms, attached to the ground rock, present higher MC. Indeed, most of the old biological attacks were detected on these elements.

408.40–606.70 kg/m^3 density range was obtained from 28 samples, which means 505.51 kg/m^3 average value and 415.78 kg/m^3 5th percentile value. The obtained density values have good correlation with the visual grading results.

The MST test permits the MOE prediction, with interesting correlation. An average value of 8522 MPa was provided by this test. 39 out of 1218 timber members were tested, a little more than 3 % of the total timber elements. The value could be slightly penalized because of the performance of few tests. This test implementation is somewhat difficult and needs auxiliary means. For avoiding penalization good pieces selection or the realization of many more tests is required. In any case, the MOE average value obtained by this test is about 15 % lower than visual grading results.

Resistograph® provides very local information. It was used mainly to check concealed areas. Results confirmed the generally good quality of the wood, as suggested by the visual inspection. Moreover, timber members located underground showed the largest density loses, as expected from the location and the other tests results.

After all the diagnostic assessment work, only 5 % of the timber elements might need a large intervention such as substitution or the addition of a prosthesis (Table 3). The remaining 95 % of the original timber structure could be maintained. Most of the timber elements only require minor restoration works like wood planning and fungicide treatment.

5. Conclusions

An assessment methodology has been applied to the "Casa del Corregidor", an historic building suffering from significant constructive and functional degradation. The proposed diagnostic assessment procedure for the timber structure was tested, requiring estimation of mechanical properties and detection of deteriorated members and areas.

This procedure involves a preliminary research phase (historical research, preliminary visual survey and drawings notebook template for in situ data collection), and a detailed data acquisition and elaboration phase (geometrical reconstruction, damage drawings, initial structural analysis, instrumental analysis and detailed structural safety evaluation).

This methodology combines visual inspection with two SDT instruments, MST and Resistograph®. The results obtained by MST slightly differed from the visual inspection results, highlighting the need for careful selection of timber members, or the realization of

Table 3
Elements requiring large intervention.

Directions for further work		
	nº	%
Total structural elements	1.218	100 %
Severely affected elements		
Elements to be entirely replaced	41	3,4 %
Elements requiring prostheses	14	1,1 %
TOTAL	55	4,5 %

more in-situ tests to obtain more reliable values. Resistograph® was also a useful tool to confirm internal decays suspected by visual survey.

All 1218 timber members were inspected. Geometric evaluation both structure and cross sections were represented on scaled drawings. These descriptive plans, available for every single room section, were instrumental in understanding the overall construction and structural configuration. Singularities, natural defects, timbers decays and failures, as well as construction and mechanical damage, were mapped with a color-coded system on the descriptive plans. They provided significant information not only of local decays, but also of larger deteriorated areas. In addition, they helped to diagnose pathologies, and the decision making for the intervention. Following this assessment, the required structural intervention could be minimized, with over 95 % of the elements deemed suitable for maintenance through wood planning and fungicide treatment. Only 41 members needed to be replaced.

The combination of visual inspection and selected instrumental tests leads to more reliable prediction of mechanical properties and detection of decay. Inspection of all timber members is essential since structure failure may be caused by only one of them. However, in one-way floors where parallel joists are connected by an upper wooden slab, the number of inspected members could be reduced.

The applied methodology facilitates the necessary restoration work on the building. It allows recognizing the damaged elements that require intervention and those that can be maintained. This work methodology can be applied in other historic buildings with wooden structure to favour the conservation of the architectural heritage.

CREdiT authorship contribution statement

Gamaliel López: In situ inspection, Conceptualization, Methodology, Investigation, Writing-original draft, Writing-review and editing. **Patricia Valleado-Cordobés:** Methodology, Writing-review and editing. **José Luis Gómez:** In situ inspection, Conceptualization, Methodology. **Luis-Alfonso Basterra:** In situ inspection, Conceptualization, Methodology, Investigation, Writing-review and editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data is uploaded in Mendeley data. It is open access available. Diagnosis and Assessment of Casa del Corregidor: Survey and diagnostic drawings, resistograph testing results and wooden samples (Original data) (Mendeley Data).

Acknowledgment

The present work was made possible thanks to financial support of the Consorcio de la Ciudad de Cuenca, Spain.

References

[1] N. Macchioni, M. Brunetti, B. Pizzo, P. Burato, M. Nocetti, S. Palanti, The timber structures in the church of the nativity in Bethlehem: typologies and diagnosis, J. Cult. Herit. 13 (4 SUPPL.) (2012), https://doi.org/10.1016/j.culher.2012.10.004.
[2] F. Longo, A. Cascardi, P. Lassandro, M.A. Aiello, Thermal and seismic capacity improvements for masonry building heritage: a unified retrofitting system, Sustainability 13 (3) (2021) 1111, https://doi.org/10.3390/SU13031111.
[3] C. Biagini, P. Capone, V. Donato, N. Facchini, Towards the BIM implementation for historical building restoration sites, Autom. Constr. 71 (2016) 74–86, https://doi.org/10.1016/J.AUTCON.2016.03.003.
[4] U.K. Zolkafli, Z. Yahya, N. Zakaria, F.W. Akashah, A.S. Ali, Restoration of historical timber building: a Malaysian case study, Struct. Surv. 33 (4–5) (2015) 309–321, https://doi.org/10.1108/SS-01-2015-0004.
[5] V. Bucur, Nondestructive Characterization and Imaging of Wood, Spinger,, 2003.
[6] ICOMOS, Principles for the Preservation of Historic Timber Structures, Icomos, no. October, 1999.
[7] EN 17121, Conservation of cultural heritage. Historic timber structures." European Committee for Standardization (CEN), Brussels, 2020.
[8] H. Cruz, et al., Guidelines for on-site assessment of historic timber structures, Int. J. Archit. Herit. 9 (3) (2015), https://doi.org/10.1080/15583058.2013.774070.
[9] H.S. Sousa, J.M. Branco, P.B. Lourenço, A holistic methodology for probabilistic safety assessment of timber elements combining onsite and laboratory data, Int. J. Archit. Herit. 10 (5) (2016), https://doi.org/10.1080/15583058.2015.1007177.

[10] M. Riggio, D. D'Ayala, M.A. Parisi, C. Tardini, Assessment of heritage timber structures: review of standards, guidelines and procedures, J. Cult. Herit. 31 (2018), https://doi.org/10.1016/j.culher.2017.11.007.
[11] B. Kasal, In-situ assessment of structural timber: state-of-the-art, challenges and future directions, Adv. Mater. Res. (2010), https://doi.org/10.4028/www.scientific.net/AMR.133-134.43.
[12] B. Faggiano, M.R. Grippa, A. Marzo, F.M. Mazzolani, Experimental study for non-destructive mechanical evaluation of ancient chestnut timber, J. Civ. Struct. Health Monit. 1 (3–4) (2011), https://doi.org/10.1007/s13349-011-0011-y.
[13] T.P. Nowak, J. Jasieńko, K. Hamrol-Bielecka, In situ assessment of structural timber using the resistance drilling method - evaluation of usefulness, Constr. Build. Mater. 102 (2016), https://doi.org/10.1016/j.conbuildmat.2015.11.004.
[14] M. Riggio, et al., In situ assessment of structural timber using non-destructive techniques, Mater. Struct. /Mater. Et. Constr. 47 (5) (2014), https://doi.org/10.1617/s11527-013-0093-6.
[15] L.A. Basterra, L. Acuña, M. Casado, G. Ramón-Cueto, G. López, Diagnosis and assessment of timber structures using nondestructive techniques: application to the Plaza Mayor in Chinchón (Madrid), Inf. De. la Constr. 61 (516) (2009), https://doi.org/10.3989/ic.09.016.
[16] UNE 41808, Existing wood structures. Graphic representation system of the constructive state of the existing wood structures." Spanish Committee for Standardization (AENOR), Madrid, 2013. [Online]. Available: www.aenor.es.
[17] G. López, P. Vallelado-Cordobés, J.L. Gómez-Royuela, L.-A. Basterra, Diagnosis and assessment of Casa del Corregidor: survey and diagnostic drawings, resistograph testing results and wooden samples, Mendeley Dataa (2023), https://doi.org/10.17632/7kwnrw4g4f.3.
[18] F. Arriaga Martitegui, G. Íñiguez González, M. Esteban Herrero, I. Bobadilla Maldonado, Large cross section sawn timber for structural use and its singularities, Inf. De. la Constr. 59 (506) (2007), https://doi.org/10.3989/ic.2007.v59.i506.505.
[19] M.C. García, J.I.F.-G. Seco, E.H. Prieto, Improving the prediction of strength and rigidity of structural timber by combining ultrasound techniques with visual grading parameters, Mater. De. Constr. 57 (288) (2007).
[20] UNE 56544, Clasificación visual de la madera aserrada para uso estructural Madera de coníferas." Spanish Committee for Standardization (AENOR), Madrid, 2022. [Online]. Available: www.une.org.
[21] EN 1912, Structural Timber. Strength classes. Assignment of visual grades and species." European Committee for Standardization (CEN), Brussels, 2012. [Online]. Available: www.aenor.es
[22] EN 13183–2, Moisture content of a piece of sawn timber: part 2: estimation by electrical resistance method." European Committee for Standardization (CEN), Brussels, 2002.
[23] EN 384, Structural timber. Determination of characteristic values of mechanical properties and density." European Committee for Standardization (CEN), Brussels, 2016.
[24] U. Dackermann, et al., In situ assessment of structural timber using stress-wave measurements, Mater. Struct. /Mater. Et. Constr. 47 (5) (2014), https://doi.org/10.1617/s11527-013-0095-4.
[25] J.-A. Balmori, L. Acuña, and L.-A. Basterra, Study of the influence of the fiber direction in the ultrasound waves' propagation rate (fakopp) through structural timber of 'Pinus radiata D. Don.' and 'Pinus sylvestris L.,'" in *Congreso Euro-Americano REHABEND*, Burgos, May 2016. [Online]. Available: ⟨http://www3.uva.es/maderas/⟩.
[26] J. Jasieńko, T. Nowak, K. Hamrol, Selected methods of diagnosis of historic timber structures - Principles and possibilities of assessment, Adv. Mater. Res. 778 (2013), https://doi.org/10.4028/www.scientific.net/AMR.778.225.
[27] J. Pošta, P. Ptáček, R. Jára, M. Terebesyová, P. Kuklík, and J. Dolejš, CORRELATIONS AND DIFFERENCES BETWEEN METHODS FOR NON-DESTRUCTIVE EVALUATION OF TIMBER ELEMENTS".
[28] D. Van Duong, J. Matsumura, Within-stem variations in mechanical properties of Melia azedarach planted in northern Vietnam, J. Wood Sci. 64 (4) (2018) 329–337, https://doi.org/10.1007/S10086-018-1725-9/FIGURES/5.
[29] S.Y. Wang, J.H. Chen, M.J. Tsai, C.J. Lin, T.H. Yang, Grading of softwood lumber using non-destructive techniques, J. Mater. Process Technol. 208 (1–3) (2008) 149–158, https://doi.org/10.1016/J.JMATPROTEC.2007.12.105.
[30] F. Arriaga, D.F. Llana, M. Esteban, G. Íñiguez-González, Influence of length and sensor positioning on acoustic time-of-flight (ToF) measurement in structural timber, Holzforschung 71 (9) (2017) 713–723, https://doi.org/10.1515/hf-2016-0214.
[31] EN 338, Structural Timber. Strength classes." European Committee for Standardization (CEN), Brussels, 2016. [Online]. Available: www.aenor.es.
[32] F. Arriaga, G. Íñiguez-González, M. Esteban, F. Divos, Vibration method for grading of large cross-section coniferous timber species, Holzforschung 66 (3) (2012) 381–387, https://doi.org/10.1515/hf.2011.167.
[33] T. Tannert, et al., In situ assessment of structural timber using semi-destructive techniques, Mater. Struct. /Mater. Et. Constr. 47 (5) (2014), https://doi.org/10.1617/s11527-013-0094-5.
[34] J.M. Branco, M. Piazza, P.J.S. Cruz, Structural analysis of two King-post timber trusses: non-destructive evaluation and load-carrying tests, Constr. Build. Mater. 24 (3) (2010), https://doi.org/10.1016/j.conbuildmat.2009.08.025.
[35] P.B. Lourenço, A.O. Feio, J.S. Machado, Chestnut wood in compression perpendicular to the grain: non-destructive correlations for test results in new and old wood, Constr. Build. Mater. 21 (8) (2007), https://doi.org/10.1016/j.conbuildmat.2006.07.011.
[36] C. Ceraldi, V. Mormone, E. Russo Ermolli, Resistographic inspection of ancient timber structures for the evaluation of mechanical characteristics, Mater. Struct. /Mater. Et. Constr. 34 (1) (2001), https://doi.org/10.1007/bf02482201.
[37] M. Kloiber, J. Tippner, J. Hrivnák, Mechanical properties of wood examined by semi-destructive devices, Mater. Struct. /Mater. Et. Constr. 47 (1–2) (2014), https://doi.org/10.1617/s11527-013-0055-z.
[38] L. Acuña, et al., Application of resistograph to obtain the density and to differentiate wood species, Mater. De. Constr. 61 (303) (2011), https://doi.org/10.3989/mc.2010.57610.
[39] UNE-EN 1995–1-1, Eurocode 5: Design of timber structures Part 1–1: General Common rules and rules for buildings." Asociación Española de Normalización (AENOR), 2016. [Online]. Available: www.une.org.
[40] C.T.E. DB-SE, Código Técnico de la Edificación. Documento Básico Seguridad Estructural, Minist. De. Fom. (2019).