Cabaleiro M., Branco J.M., Sousa H.S., Conde B. (2018) First results on the combination of laser scanner and drilling resistance tests for the assessment of the geometrical condition of irregular cross-sections of timber beams. *Materials and Structures* 51:99. (doi.org/10.1617/s11527-018-1225-9)

The final publication is available at link.springer.com:

<https://link.springer.com/article/10.1617%2Fs11527-018-1225-9>

FIRST RESULTS ON THE COMBINATION OF LASER SCANNER AND DRILLING RESISTANCE TESTS FOR THE ASSESSMENT OF THE GEOMETRICAL CONDITION OF IRREGULAR CROSS-SECTIONS OF TIMBER BEAMS.

Manuel Cabaleiro^{1*}, Jorge M. Branco², Hélder S. Sousa² and Borja Conde¹

¹Department of Materials Engineering, Applied Mechanics and Construction, School of Industrial Engineering, University of Vigo, C.P. 36208, Vigo, Spain.

²ISISE, Department of Civil Engineering, University of Minho, 4800-058 Guimarães, Portugal

*Corresponding author: mcabaleiro@uvigo.es; tel: +34 986 813659. Fax: +34 986 813663

Abstract

Old timber structures often present damaged elements with irregular cross-sections, hidden surfaces and even with loss of material due to decay. Within that scope, in this paper, a new methodology based on the combination of laser scanner and drilling resistance tests is proposed and developed with the aim of analyzing the apparent and resistant sections of timber beams with hidden surfaces and irregular cross-section affected by decay. The proposed methodology was initially calibrated with tests made on a timber beam within a laboratory environment and, then, its feasibility was tested on a case study regarding the timber roof of the Guimarães Castle keep. The results confirm the suitability of this methodology for assessment of the present geometrical properties of timber elements with an average error of 1.5% and 4.5%, respectively, in the calculation of the apparent section area and inertia.

Keywords: Resistant section, LIDAR, deterioration degree, wood, timber structures

1 INTRODUCTION

In the large majority of historical buildings, timber was present and used as a construction material. In most of the cases (e.g. houses, castles, churches), timber was mainly used in the construction of roofs and coverings. However, examples of constructions made almost entirely of timber may also be found. Therefore, and taking into account its historical and social importance, it is essential to properly document and preserve these structures. Presently, HBIM (Historic Building Information Modelling) tools are used for the documentation of these historical buildings where, among other data, the geometry of the structural elements is detailed and analysed. In the case of old timber elements, particularly roof elements, a large variation on the geometry of the elements' cross-section may be found as detailed in [Lourenço *et al.* \[1\]](#). The irregular shape of the cross-section may be due to the construction technique itself. In some cases, it maintained the shape of the log, therefore leading to round cross-sections. In other cases, external damage or decay may have led to irregularities in the shape of the cross-sections, not only locally but also along the length of the element. Moreover, it is common to find timber elements that are not longitudinally straight and even, in some cases, presenting a large deformation or twist. These anomalies are a great obstacle for an onsite assessment when performing a detailed geometrical survey, since it requires more resources and time.

Nowadays, laser scanning is one of the most promising techniques for gathering geometric data about buildings and its elements [\[2\]](#). Several researches have used data collected from laser scanning for structural modelling to build geometrical models of the elements. Among these works there are researches focused on the automation of the modelling process from Lidar data. Examples using Lidar data include: the generation of semantically rich 3D building models [\[3\]](#), the proposal of new methods for the automatic generation of metal connections [\[4\]](#), modelling of building interiors for as-built BIM [\[5\]](#), the automatic extraction of BIM components of the buildings [\[6\]](#), the BIM implementation for historical building restoration sites [\[7\]](#), or the automatic building accessibility diagnosis using point clouds [\[8\]](#). Applications of this technique

have also been carried out in the field of masonry buildings, such as arch bridges [9, 10], churches [11] or even of metal structures [12], aiming at their structural modelling. Moreover, attempts for a semi-automatic generation of the finite element model of historical constructions for subsequent structural analysis have been carried out [13]. The laser scanner has been used, in another relevant field of application which is the structural inspection and monitoring [14-16]. In the specific field of timber structures, the laser scanner has also been used for geometrical analysis [17-20]. However, research in the subsequent structural analysis using that data is still in at an early stage of development. For example, in the field of structural health control in timber building using Lidar data, Cabaleiro *et al.* [21] has presented an algorithm for the detection and control of cracks in timber beams, whereas in Cabaleiro *et al.* [22] the modelling of irregular cross-section timber elements was also made. In that work, the edges of different sections of a timber beam were calculated from the cloud of points obtained by a laser scanner and by applying an alpha-shape based algorithm. Subsequently, with the obtained data the geometric properties of each of the cross-sections were calculated. However, that methodology has the drawback that hidden faces of the cross-section, which is common in floor beams or in roof elements, are assumed as a straight line between the last detected points of the adjacent visible faces. This assumption often leads to smaller cross-section areas for the calculated section compared to the real apparent section of the beam. Therefore, obtaining the real geometry of the beam's hidden surface represents a major problem which requires further research, especially in the case of structural analysis of historical buildings.

To tackle this problem, it is first necessary to understand the factors that may influence the measurement of the geometry of timber elements and the current methods that are being used. As discussed in Lourenço *et al.* [1], a large variation in the cross-section geometry may exist when dealing with older buildings since irregular shapes (due to the cutting process or lack of material) and decay are often present. Several pathological agents that induce decay may affect timber. Besides the abiotic agents (e.g. solar radiation, wind exposure, water variation, external damage), timber elements are also exposed to decay by biotic agents such as fungi and xylophage insects.

Timber decay caused by biotic agents is conditioned by the onsite values of temperature and humidity and its evolution along time may seriously decrease the cross-section area and compromise the structural performance of the element [23-24]. The decay progression may be visible from the exterior surface, but may also begin and develop in the interior of the cross-section. Therefore, increasing the need for testing the integrity of the cross-section not only from its visible faces but also from its interior. In order to assess the state of conservation of timber elements of historical constructions onsite, without inducing considerable damage to the element itself, several semi-destructive tests (SDT) or non-destructive tests (NDT) can be used, which can after be used to update the information for a structural assessment [25]. Ultrasonic techniques, acoustic emission, stress waves, X-rays, Gamma rays are among the examples of NDTs, whereas pin penetration, screw withdrawal, drilling resistance and hardness tests are among the SDTs [26, 27]. Drilling resistance tests will be further discussed in this work due to its applicability to assess locally the geometry of a timber cross-section and the depth of decay [26, 28].

Drilling resistance is a test based on the micro-drilling of wood at a constant velocity by a standard drill, either per cutting edge of a drill bit or per revolution, while measuring the necessary energy to perform it. It might be used to obtain density profiles but it also allows to evaluate the full size of the specimen's cross-section [29]. This method also permits the detection of internal defects, such as knots, inner voids, cracks, inclusions or decay taking into account the relative energy change (either increase or decrease). Drilling resistance tests are useful to estimate the depth of the exterior layer decayed by biotic agents and of internal regions affected either by insects, fungi or both and, thus, the local loss of a resistant cross-section. Nevertheless, it should be noted that the measurements are made only for the drilling path of the device needle, thus obtaining a local evaluation of the element. This also leads to the need to take into account the entry and exit points of the needle and assess if there was any deviation from the expected drilling path. This may be difficult to assess and may cause significant errors especially for irregular cross-sections. Due to these limitations, drilling resistance tests are often combined

with other SDTs or NDTs for onsite assessment, such as in the cases of [Lechner *et al.* \[28\]](#), [Liao *et al.* \[30\]](#) and [Branco *et al.* \[31\]](#). Multiple drilling resistance measurements with different directions (vertical and horizontal) may be performed on a single cross-section allowing to define a two-dimensional map of the location of decayed regions (both superficial and internal). Nevertheless, the combination of different methods aiming at improving the determination of the apparent and resistant cross-section geometry of timber elements with hidden surfaces and/or irregular cross-section shapes and lack of material is still at an early stage of development. Moreover, the combination of drilling resistance and laser scanner tests has not yet been fully considered for these cases.

By taking into account the need for a better definition of the cross-section geometry of irregularly shaped timber elements with hidden surfaces and lack of material, the objective of this work is to propose and apply a new methodology based on the combination of laser scanner and drilling resistance that is suitable for onsite applications. This methodology aims to obtain the apparent section perimeter, area and moment of inertia, as well as its residual cross-section related to the decay level of a timber element for structural engineering purposes.

2 METHODOLOGY

For the determination of the apparent (exterior surface perimeter) and resistant cross-sections of wooden beams with irregular cross-sections, the combination of laser scanning with measurements made with a drilling resistance equipment was proposed. [Figure 1](#) presents the methodology used for the combination of these tests.

The methodology is divided in three main steps: 1) in situ testing; 2) data processing; 3) calculation of parameters. The first step comprises of the in situ testing which starts with the resistance drilling tests. The sections determined as critical, either by their position in the beam or by their visible deteriorated state, are tested by submitting it to drilling resistance tests. For example, in beam girders or roofs, the critical points correspond usually to the end supports and

the middle of the beams. The tests consider two horizontal drillings starting at approximately one third of each lateral face and two vertical drillings starting at approximately one third of the bottom face. In order to obtain a precise location of the drilling resistance measurements, the entry and exit points of the drilling needle are marked (when the surface is visible and accessible). For this purpose, targets for the laser scanning are placed on the entry and exit points of the resistance drilling test (see Figure 6) which will allow to find these positions in the cloud of points. The location reference of each resistance drilling test is labeled at each target. Only after, the procedure continues with the laser scanning. The beam is scanned on at least two opposite vertical faces with a suitable inclination of the laser scanner with respect to the vertical face of the beam ($45^\circ \pm 5^\circ$ of inclination is recommended).

The second step of the methodology deals with the data processing (Figure 2). Initially, the cloud of points of the laser scanning is registered and analyzed. The different scans of the beam are aligned and registered in a single cloud of points with only a reference system. Consequently, the regions of the cloud of points not corresponding to the beam and the overlapping points are deleted, leaving only the beam to be analyzed. Afterwards, the sections which were previously tested by the drilling resistance tests are detected in the cloud of points. The cloud of points of the beam is sliced on the location of each of those cross-sections and the entry and exit points of the drilling resistance test needle are identified. On each of the obtained sections the algorithm proposed by Cabaleiro et al. [22] is applied and the contour of the cross-section is obtained. The coordinates of the entry and exit points of the needle are also calculated. At this moment, the drilling resistance test data is added to the process. On the non-visible side of the beam, the point of exit of the needle in the contour is calculated by incorporating the length value obtained with the drilling resistance profile and locating it based on the corresponding entry point of the needle obtained in the previous step. If the exit surface is not visible (e.g the upper surface of a beam) (Figure 2), the calculation of the coordinates of these points is given by Eq. 1:

$$(x_{iL}, y_{iL}) = (x_{iP}, (y_{iP} + L_i)) \quad \text{Equation 1}$$

where (x_{iL}, y_{iL}) are the coordinates of the theoretical point i of exit of the needle, on the non-visible surface of the beam, x_{iP} is the x coordinate of the point of entry of the needle of drill number i , y_{iP} is the y coordinate of the point of entry of the needle of drill number i , and L_i is the length of the drill obtained with the drilling resistance test in drill number i .

The last step of the methodology comprises in the calculation of the geometric properties of each cross-section. The laser scanner apparent cross-section is obtained through the laser scanning data and the area A_L is calculated according to the method proposed by Cabaleiro *et al.* [22]. The apparent section A_L (apparent area from laser scanner) is calculated applying an alpha-shape function in the contour obtained with the projected cloud of points. The upper surface, as it is not visible and thus not existent in the cloud of points, is determined by connecting the upper edges with a straight line (points $P_b (x_b, y_b)$ and $P_e (x_e, y_e)$) [22] (Figure 2).

At this moment, the data obtained with laser scanning and with the drilling resistance tests are combined. The area A_H (added area from the drilling resistance tests) is calculated according to equation 2. The area A_H represents the area of the polygon formed by points $P_b (x_b, y_b)$ and $P_e (x_e, y_e)$ of the edge of the contour obtained in the previous step and the two theoretical points of exit of the drilling resistance tests $P_{1L} (x_{1L}, y_{1L})$ and $P_{2L} (x_{2L}, y_{2L})$ of the non-visible surface (see Figure 2).

$$A_H = \frac{1}{2} \begin{bmatrix} x_{1L} & y_{1L} \\ x_{2L} & y_{2L} \\ x_e & y_e \\ x_b & y_b \end{bmatrix} \quad \text{Equation 2}$$

The total apparent area A_A (combination of the data obtained with the laser scanner and the drilling resistance tests) is obtained by adding the apparent area given by the laser scanner, A_L , and the area A_H , as described in equation 3.

$$A_A = A_L + A_H \quad \text{Equation 3}$$

A_A corresponds to the area and representation of the cross-section on which all the geometric properties of the section of the beam can be calculated.

As it can be observed in [Figure 3](#), with the proposed methodology that combines the data obtained with laser scanner and drilling resistance tests, a more precise calculation of the apparent sections of a timber beam can be obtained.

Besides the apparent cross-section, the drilling resistance tests allow to calculate the residual cross-section (A_R), also called resistant section, as well as the presence and depth of decay. The resistant section, obtained through the drilling resistance tests, is of extreme importance for the calculation of the safety level of an existing structure composed by timber elements. Decay reduces the mechanical properties of the timber element and must be accurately accounted in a safety assessment analysis.

The resistant section obtained by the resistance drill is calculated taking into account the length of deterioration obtained on each performed drilling profile (L_{dp} and L_{dl}) ([Figure 4](#)). The length of the profile is obtained from the coordinates of the points of entry and exit of the drills and the line that these points form. The length of deterioration was obtained considering a three step procedure. The first step consisted in performing a visual inspection to locate and identify superficial decay. The surface visual inspection was complemented by taking small splinters of wood (only removed after both the drilling resistance and laser scanner tests were made, as to avoid influencing the measurement of the geometry of the cross-section). The second step consisted in the analysis of the cumulative integral of the drilling resistance profile along the length of the drilling path, where each point that had a significant change (difference of more than 5% from the mean value obtained until that point) was marked. With that information, on the third step, an expert detected the areas considered as deteriorated. The first two steps are intended to decrease the subjectivity inherent to the expert decision. This procedure was also used in [24], where in that case the sections were cut on the test cross-section and the results of the procedure were verified directly on the timber piece. The length of the damaged section,

obtained by this procedure, is deducted at the points of entry and exit, thus providing the new points that delimit the polygon which forms the resistant area of each section. To the points that define the resistant polygon (Figure 4), the Gauss equation for area calculation (Equation 4) is applied for a polygon in which the coordinates of its vertices are known.

$$A = \frac{1}{2} \begin{vmatrix} x_1 & y_1 \\ x_2 & y_2 \\ \vdots & \vdots \\ x_n & y_n \end{vmatrix} \quad \text{Equation 4}$$

where A is the area of the polygon, x is the horizontal coordinate of each point (abscissa), y the vertical coordinate of each point (ordinate), and n the number of polygon vertices. When in the section there are two horizontal drillings and two vertical drillings the calculation of the residual cross-section A_R according to the drilling resistance tests is given according to Equation 5.

$$A_R = \frac{1}{2} \left| \sum_{i=1}^7 x_i y_{i+1} + x_8 y_1 - \sum_{i=1}^7 x_{i+1} y_i - x_1 y_8 \right| \quad \text{Equation 5}$$

where A_R is the residual cross-section calculated according to the resistance drill path, x_i is the abscissa of each point that define the polygon of the residual cross-section, y_i is the ordinate of each point that define the polygon of the residual cross-section. The definition of A_R allows to obtain the area on which all the geometric properties of the resistant section of the beam can be related, such as the moment of inertia

In order to calculate the apparent section in beams with irregular section using only the drilling resistance tests, the points of the coordinates of entry and exit of the drills in the beam are used directly in Equation 4.

Based on the geometrical data of apparent section A_A and the residual cross-section A_R , the degree of deterioration DD can be calculated according to the following equation:

$$DD = \left(\frac{A_A - A_R}{A_A} \right) 100 \quad \text{Equation 6}$$

where A_A is the apparent section calculated according to the combination of the data obtained with the laser scanner and the drilling resistance tests and A_R is the residual cross-section calculated according to the resistance tests as obtained in Eq. 5.

In order to assess the reliability of the proposed method, different timber elements were tested in different conditions, such as different accessibility, visibility of surfaces and degree of degradation. To each case, the described methodology was applied by calculating the area and inertia considering the coordinates of the exterior points of the cross-sections obtained by each test (drilling resistance or laser scanner) and their combination. The results are presented regarding the mean value error obtained for all sections of the same element.

3 MATERIALS AND EXPERIMENTAL CAMPAIGN

During the experimental campaign two main equipment were used, namely the laser scanner and the drilling resistance test equipment. A terrestrial laser scanner FARO Focus 3D was used to collect the cloud of points for all tests. This specific laser scanner measures distances over a range of 0.6–120 m, with a nominal precision of ± 2 mm.

For the drilling resistance tests, a Resistograph® 3450 equipment was used, which has a drilling needle with 3 mm diameter at the cutter of the drill bit and 1.5 mm diameter along the shank. The drilling needle advances at a constant speed of 30 cm/min, turning at 1500 rpm.

With the described equipment, the methodology proposed in this work was applied in a controlled laboratory environment regarding a short length beam. The chosen element had an irregular cross-section and visible decay. All the surfaces were visible and easily accessible for inspection and testing, both for scanning as well as for drilling resistance tests. The aim of this test was to calibrate the proposed methodology by assessing its feasibility and accuracy of results. After, field tests were made so as to verify the applicability of this methodology to onsite elements. The tests were made on a timber roof structure of a heritage building. In this

case study, only three of the faces were visible and accessible for testing, as the top surface was not possible to be laser scanned. This is a common situation for timber roof structures.

3.1 Laboratory test.

In the laboratory test, an irregular cross-section timber beam was tested using the drilling resistance method. The beam had a length of 1100 mm and an average cross-section geometry of $220 \times 220 \text{ mm}^2$. This beam evidenced clear signs of deterioration by insect attack (Figure 5). The beam originated from a demolished old building, built in the 19th century. This beam was submitted to two horizontal and two vertical drillings per section in five different sections along its length. The drillings were equally spaced on each surface, thus the measurements were taken on one third of the height of the surface from each edge of the cross-section. Measurements made on superficial local defects, such as visible knots, were avoided during each test.

After the drilling resistance tests were made, each entry and exit points were marked with a $40 \times 40 \text{ mm}^2$ target (Figure 6), as to obtain the exact entry and exit points of the drill when measuring the section by laser scanning. Following that procedure, the beam was placed at 1500 mm from the ground level and scanned at an inclination to the vertical surfaces of 45° and 75° (Figure 6). The mean density of the cloud of points was of 1.5 mm. The top surface was also scanned so as to obtain the full contour of each of the analysed cross-sections. This shape, corresponding to the perimeter of the cross-section, is obtained with precision because the laser scanner technique can be made to all faces. This is possible in a laboratory environment where the laser scanner may be placed in different locations, allowing that every single face is completely visible at least in one location during the measurements. In these conditions the laser scanner measures the geometry of the section with an error of approximately only 3%, as demonstrated in Cabaleiro *et al.* [22]). Also in similar applications, other works as Gonzalez-Jorge *et al.* [34] or Cabaleiro *et al.* [33] show that the measurement error made by the laser scanner is very small. For that reason, the shape derived from the laser scanner when all faces are visible, is used as benchmark value when comparing to the cases where there is no information

on the geometry of the top face of the beam. By this process it is intended to compare the geometry of the beam obtained in laboratory conditions, where information on all the faces may be measured and obtained (thus assumed to be representative of the real shape of that cross-section), with the onsite conditions where the top face of the element is often not visible or non-accessible. Comparisons were made with this value and with those obtained when using only laser scanning (without assessing the top surface) and when using the combination of the two tests (laser scanner and drilling resistance).

3.2 Field test

The reliability and application of the proposed method in order to identify the shape and geometrical properties of irregular cross-sections from timber beams were checked in a field test. The selected case study corresponds to the timber roof of Guimarães medieval castle keep. The castle is associated to the origins of the Portuguese nation and was initially built in the 10th century as to defend the local monastery from invasions. The area of the castle is delineated by fortified walls. It is in the shape of a pentagram which includes eight rectangular towers, a military square and the central keep. The keep itself is a 27 m high granite structure with a quadrangular plant. The castle was left without significant maintenance during the 18th and 19th centuries and only in the early 20th century was it listed as a protected national monument. Restoration works began in 1937 and since then the castle was submitted to different interventions in order to maintain its structural integrity.

The timber roof of the keep has eight horizontal timber beams that connect the main masonry core of the building to the exterior walls. The beams have irregular cross-sections, having an average cross-section dimension of $340 \times 340 \text{ mm}^2$, placed at a height level of 5.5 m. The beams present different levels of decay (by insect attack) between them. However, no active decay phenomenon was detected during the onsite inspection, which indicates that the decay found was due to past events.

By taking into account the different levels of decay and irregularity of the cross-sections, three elements were selected to use the method proposed in this work for definition of the cross-sections parameters. The beams were selected considering the elements with higher level of decay and higher irregularity of the cross-section along the length of the element. Two sections per beam were measured and tested using the drilling resistance tests. The sections corresponded to one of the supports of the beam (either the support to the central core or to the exterior wall, whichever had the highest level of irregularity) and the central cross-section ([Figure 7](#)). These cross-sections also correspond to the critical sections in a structural analysis regarding the sections where higher concentration of stresses may be found.

Laser scanning was made to all visible faces from the floor level (lateral and bottom surfaces) of all beams leaving the top surface without being scanned due to accessibility limitations. The inclination of the laser scanner with respect to the beams was around 45°. The thickness of the top surface on each cross-section was manually measured using a calliper and a measuring tape, while a marked try square in combination with a spirit level was used to measure wane and the angles between the top and both lateral surfaces of the timber beam. Since these measurements were made with the objective of providing a benchmark value, they were repeated by three separate inspectors. Determination of the level of error was made after comparing this value with those obtained when using only laser scanning (without assessing the top surface) and when using the proposed method that combines laser scanning and drilling resistance tests.

4 RESULTS AND DISCUSSION

After both the laboratory and onsite tests, the measurements of each test were combined, according to the proposed method, in order to obtain the geometrical properties of the analyzed cross-sections. The output results were compared with the measurements made to each cross-section and the details from this analysis are provided in the following points.

4.1 Laboratory tests

The results obtained in the laboratory are presented in [Table 1](#) for the five tested sections of one timber beam.

Table 1. Results for each section of the tested elements obtained in laboratory conditions.

Section	Parameter	Exterior section (benchmark)	Drilling resistance	Laser scanner (45°)	Laser scanner (45°) + Drilling resistance	Laser scanner (75°)	Laser scanner (75°) + Drilling resistance	Residual cross- section
L.1	area (cm ²)	476.6	429.7	455.1	472.2	358.7	453.7	289.8
	I _x (cm ⁴)	16437	12946	13634	16203	7630	14656	7059
	I _y (cm ⁴)	20115	16866	17149	19663	14661	18542	6627
L.2	area (cm ²)	469.2	435.3	423.0	464.4	383.0	458.7	284.3
	I _x (cm ⁴)	16384	13671	13016	16032	9195	15567	7043
	I _y (cm ⁴)	19275	16861	17323	18802	15598	18369	6675
L.3	area (cm ²)	488.1	454.4	426.9	479.7	411.4	475.5	291.0
	I _x (cm ⁴)	17484	16194	12113	16707	11134	16493	7043
	I _y (cm ⁴)	21277	16912	18631	20735	17477	20056	6675
L.4	area (cm ²)	468.6	449.4	426.3	462.3	349.0	451.8	273.3
	I _x (cm ⁴)	16868	15485	12527	16503	7131	15527	6374
	I _y (cm ⁴)	18418	16935	16392	17874	13987	17313	5918
L.5	area (cm ²)	439.0	399.7	400.3	437.2	366.1	433.1	236.9
	I _x (cm ⁴)	14526	11827	12518	14409	9666	14209	4799
	I _y (cm ⁴)	16627	13809	13809	16468	12784	16059	4295

From [Table 1](#), it can be seen that the apparent cross-section area obtained by using only the results from the drilling resistance tests presented an average error of 7.4% (with maximum of 10%). When using only the laser scanner measurements at 45° inclination an average error of 8.7% (maximum of 12.5%) was found. When combining the laser scanning (measurement at 45°) with the drilling resistance tests, the average error significantly decreases to 1.1% (with a maximum of 1.7%). Considering the same procedure for the calculation of the moments of inertia [32], it was found that the average error when using only the drilling resistance tests is 14.2% (with a maximum of 21.4%) for I_x (moment of inertia respect to the horizontal axis X), whereas the values using only the laser scanning are of 21.9% (with a maximum 30.7) for inclinations of 45°. In this case, the combination of laser scanning and drilling resistance tests produced an average error of 2.3% (with a maximum of 4.5%) ([Figure 8](#)). From analyzing the

results found for laboratory conditions, the use of the combination of laser scanner with drilling resistance tests in relation to the use of only the laser scanner at 45°, can improve the calculation of the apparent area in more than 8% and by more than 15% for the case of moment of inertia.

The results show a mean reduction of resistant cross-section of approximately 41% in terms of area and approximately 61% for inertia (I_x). This is a considerable reduction revealing that the element was in a poor conservation state with significant decay due to insect attack. It should also be noted that the element already presented visible signs of decay and thus the results of the drilling resistance tests are consistent with the visual inspection. The mean value of decay depth found for all sections was 26 mm (with a mean maximum of 39 mm).

When using only the laser scanner measurements at 75° inclination, regarding the calculation of the apparent cross-section area an average error of 20.2% (maximum of 25.5%) was found and regarding the calculation of the moments of inertia an average error of 45,2% (maximum of 57.7%) was found (Figure 9). Regarding the combination of the tests (laser scanner at 75° and drilling resistance tests) in relation to the use of only the laser scanner at 75°, it can improve the calculation of the apparent area in more than 25% and by more than 50% for the case of moment of inertia.

As it can also be observed from the results, the difference of percentage error obtained between using the laser scanner at 45° or 75° is very significant. The percentage error doubles when using only the laser scan to calculate the apparent section. In the case of the combination of laser scanner and drilling resistance tests, if the inclination angle is changed from 45° to 75° the percentage error also increases but, in this case, the change is considerably smaller not exceeding a 3% difference on average for area calculation and 7% difference on average for the moment of inertia (Figure 8-9).

When applying only the laser scanning, it was demonstrated that the choice of inclination may significantly affect the accuracy of the measurements, reaching a variation from 8.7% to 20.2%

in the measurement of the cross-section area. In this study, it was found that the inclination of 45° was more adequate.

By considering the measurements of the drilling resistance tests of the decayed areas, the average degree of decay of the residual cross-section (A_R) with respect to the exterior section (benchmark) was 41.3%. When considering the proposed method, a similar value was of 39.5% was obtained.

4.2 Test in beams of a building

The results of the application of the method in a case study were analyzed and compared to the measurements made onsite. The results are presented in [Table 2](#).

[Table 2](#). Results for each section of the tested elements obtained in the field test.

Section	Parameter	Exterior section (benchmark)	Drilling resistance	Laser scanner (45°)	Laser scanner (45°) + Drilling resistance	Residual cross-section
1.1	area (cm ²)	1118.9	1009.1	927.7	1110.2	862.2
	I _x (cm ⁴)	112216	90161	62719	109950	67288
	I _y (cm ⁴)	94879	73869	83069	93461	53000
1.2	area (cm ²)	1006.3	846.4	842.6	986.3	764.6
	I _x (cm ⁴)	97230	65609	55386	89616	54440
	I _y (cm ⁴)	74576	51022	67570	73975	40970
3.1	area (cm ²)	669.1	604.3	631.2	666.7	528.5
	I _x (cm ⁴)	36803	29092	30736	36442	22595
	I _y (cm ⁴)	36065	29591	34796	35852	22374
3.2	area (cm ²)	729.1	690.9	644.3	719.9	610.2
	I _x (cm ⁴)	42896	39349	30349	41538	31316
	I _y (cm ⁴)	43855	37987	39287	42936	28929
6.1	area (cm ²)	834.4	754.9	675.6	818.6	641.0
	I _x (cm ⁴)	52412	43074	27183	49289	30573
	I _y (cm ⁴)	59794	48965	52460	58890	35782
6.2	area (cm ²)	990.7	892.4	744.8	957.0	810.0
	I _x (cm ⁴)	79765	65698	34668	72743	52740
	I _y (cm ⁴)	77597	61993	61019	72116	52380

Considering the exterior geometry of the cross-sections, the results obtained in the beams of the keep in six different tested sections show, in the case of the area calculation, an average error of 10.3 % (with a maximum of 15.9%) when using only the drilling resistance tests and an average error of 16.5% (with a maximum of 24.8%) when using only the laser scanning. In this case, the combination of results led to an average error of 1.7 % (with a maximum of 3.4%). For the calculation of the moments of inertia [32], it was found that the average percentage error when using only the drilling resistance tests was 21.0% (with maximum of 32.5%) for I_x , while when using only the laser scanning, the average error was 42.8% (with a maximum of 56.6%) whereas if the combination of tests is considered, the average error decreases to 5.1 % (with a maximum of 7.8%) (Figure 10).

The mean value of decay depth found for beam 1 was 12 mm (maximum of 24 mm), while for beam 3 was 10 mm (maximum 29 mm) and for beam 6 was 13 mm (maximum 33). However, due to the size and geometry of the beams, in terms of reduction of resistant cross-section, it is seen that beam 1 is the element with higher area loss (mean decrease of 23%), whereas beam 3 is the one with lower area loss (mean decrease of 18%). Considering all elements, an overall mean of 21% of reduction of the resistant cross-section area, due to decay, was obtained using the drilling resistance tests. Although these are significant decreases, the values should be analyzed with caution, since as seen in Figure 4, the calculation of the resistant cross-section of an element using only drilling resistance tests greatly depends on the number of drilling paths specially for the corners of the element.

By considering the measurements of the drilling resistance tests by taking into account the decayed areas, the average degree of decay of the residual cross-section (A_R) with respect to the exterior section (benchmark) was 21.2%. When considering the proposed method, a similar value of 19.8% was obtained.

5 CONCLUSIONS

This work presents the proposal of a method that combines the results of drilling resistance tests and laser scanning for the analysis of geometrical properties of irregular cross-sections of timber beams affected by decay. The methodology was calibrated with the results of laboratory tests and used on a case study to verify its applicability and feasibility.

With the combination of drilling resistance tests and laser scanning it was demonstrated that, compared to the results obtained for each test separately, it is possible to increase the accuracy of the measurement of the geometric parameters to a level similar to the real cross-section measurements. With the small difference in percentage error, the method presents a valid framework for the measurement of irregular timber cross-sections on onsite elements.

For the onsite elements that present a hidden surface, which correspond to most of the practical cases, the combination of laser scanning with drilling resistance tests is a valid solution to obtain the needed data for the geometrical definition of the hidden surface. This allows to minimize the error present in the calculation of the geometrical properties, especially for the moment of inertia. By combining both tests, average percentage errors of 1.5% are obtained for the calculation of the area with maximum values not exceeding 3.5%. In the case of the calculation of the moment of inertia, the average value is lower than 5%.

It is noteworthy to mention that the main application of the drilling resistance tests is to identify weak regions in the interior of a cross-section but it can also be applied to locally verify the thickness of an element.

The application of the laser scanning also allowed to localize the measurement points of the drilling resistance tests (both entry and exit points when both surfaces are visible), permitting to analyse the drilling path of the needle and infer on possible deviations. Another important advantage was the possibility to join the local data obtained in the drilling resistance tests with a global representation of the element. In this case, not only the local definition of the cross-

sections is possible but also to represent the deformation of the beam and alignment between cross-sections [33]. Therefore, this method allows to assess the irregularity of the geometry of a cross-section at a given point, as well as the irregularity of the sections along the beam's length.

The resistant cross-section was also calculated considering the analysis of the drilling resistance measurements. Even if this work treats mainly with the measurement of the exterior geometry of elements with irregular cross-section, the combination of the drilling resistance tests with the laser scanner methods can be further developed regarding the attribution of the resistant cross-section obtained in a critical section for all sections, effectively estimated through the laser scanning, along the element even if those sections are not accessible for drilling resistance tests. Future works should address in this way.

As a final conclusion, the proposed method presents a framework that improves the onsite measurement of the geometrical properties of timber elements with irregular cross-sections with or without the presence of superficial decay.

Acknowledgments.

This work has been partially supported by the European Association of International Cooperation Galicia-North of Portugal, program IACOBUS IV through a stay at the University of Minho to M. Cabaleiro (IACOBUS IV-35563149). This work has been partially supported by the Spanish Ministry of Interior (Grant SPIP2017-02122), Spanish Ministry of Economy, Industry and Competitiveness (Grant: EUIN2017-87598), and Xunta de Galicia through grant ED431C2016-038. This work was partly financed by FEDER funds through the Competitivity Factors Operational Programme - COMPETE and by national funds through FCT Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633. This research was partially supported by ProTimber research project (PTDC/ECM-EST/1072/2014) financed by the FCT Foundation for Science and Technology.

Conflict of Interest: The authors declare that they have no conflict of interest.

References

- [01] Lourenço PB, Sousa HS, Brites RD, Neves LC (2013) In situ measured cross section geometry of old timber structures and its influence on structural safety. *Materials and Structures* 46(7):1193-1208.
- [02] Tang P, Huber D, Akinci B, Lipman R, Lytle A (2010) Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques, *Automation in construction* 19(7):829-843.
- [03] Xiong X, Adan A, Akinci B, Huber D (2013) Automatic creation of semantically rich 3D building models from laser scanner data. *Automation in Construction* 31:325-337.
- [04] Cabaleiro M, Riveiro B, Arias P, Caamaño JC, Vilán JA (2014) Automatic 3D modelling of metal frame connections from LiDAR data for structural engineering purposes. *ISPRS Journal of Photogrammetry and Remote Sensing* 96:47-56.
- [05] Jung J, Hong S, Jeong S, Kim S, Cho H, Hong S, Heo J (2014) Productive modeling for development of as-built BIM of existing indoor structures. *Automation in Construction* 42:68-77.
- [06] Wang C, Cho YK, Kim C (2015) Automatic BIM component extraction from point clouds of existing buildings for sustainability applications. *Automation in Construction* 56:1-13.
- [07] Biagini C, Capone P, Donato V, Facchini N (2016) Towards the BIM implementation for historical building restoration sites. *Automation in Construction* 71:74-86.
- [08] Balado J, Díaz-Vilariño L, Arias P, Soilán M (2017) Automatic building accessibility diagnosis from point clouds. *Automation in Construction* 82:103-111.
- [09] Conde B, Díaz-Vilariño L, Lagüela S, Arias P (2016) Structural analysis of Monforte de Lemos masonry arch bridge considering the influence of the geometry of the arches and fill material on the collapse load estimation. *Construction and Building Materials* 120:630-642.
- [10] Riveiro B, Morer P, Arias P, De Arteaga I (2011) Terrestrial laser scanning and limit analysis of masonry arch bridges. *Construction and building materials* 25(4):1726-1735.
- [11] Sánchez-Aparicio L J, Riveiro B, Gonzalez-Aguilera D, Ramos LF (2014) The combination of geomatic approaches and operational modal analysis to improve calibration of finite element models: A case of study in Saint Torcato Church (Guimarães, Portugal). *Construction and Building Materials* 70:118-129.

- [12] Conde B, Villarino A, Cabaleiro M, Gonzalez-Aguilera D (2016) Geometrical Issues on the Structural Analysis of Transmission Electricity Towers Thanks to Laser Scanning Technology and Finite Element Method. *Remote Sensing* 7(9):11551-11569
- [13] Castellazzi G, D'Altri AM, de Miranda S, Ubertini F (2017) An innovative numerical modeling strategy for the structural analysis of historical monumental buildings. *Engineering Structures* 132:229-248.
- [14] Zhang C, Arditi D (2013) Automated progress control using laser scanning technology. *Automation in Construction* 36:108-116.
- [15] Mosalam KM, Takhirov SM, Park S (2014) Applications of laser scanning to structures in laboratory tests and field surveys. *Structural Control and Health Monitoring* 21(1):115-134.
- [16] Jaafar HA, Meng X, Sowter A, Bryan P (2017) New approach for monitoring historic and heritage buildings: Using terrestrial laser scanning and generalised Procrustes analysis. *Structural Control and Health Monitoring* 24(11)
- [17] Balletti C, Berto M, Gottardi C, Guerra F (2013) Ancient structures and new technologies: survey and digital representation of the wooden dome of SS. Giovanni e Paolo in Venice, *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 5, W1: 25–30.
- [18] Oreni D, Brumana R, Georgopoulos A, Cuca B (2013) HBIM for conservation and management of built heritage: Towards a library of vaults and wooden beam floors. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 5 W1.
- [19] Fregonese L, Taffurelli L (2009) 3D model for the documentation of cultural heritage: the wooden domes of St. Mark's Basilica in Venice. *ISPRS Archives* 38:5.
- [20] Alessandri C, Mallardo V (2012) Structural assessments of the Church of the Nativity in Bethlehem. *Journal of Cultural Heritage*, 13(4):e61-e69.
- [21] Cabaleiro M, Lindenberg R, Gard WF, Arias P, van de Kuilen JWG (2017) Algorithm for automatic detection and analysis of cracks in timber beams from LiDAR data. *Construction and Building Materials* 130:41-53.
- [22] Cabaleiro M, Riveiro B, Arias P, Caamaño JC (2016) Algorithm for the analysis of the geometric properties of cross-sections of timber beams with lack of material from LIDAR data. *Materials and Structures* 10(49):4265-4278.
- [23] Brites RD, Neves LC, Machado JS, Lourenço PB, Sousa HS (2013) Reliability analysis of a timber truss system subjected to decay. *Engineering Structures* 46:184-192.

- [24] Sousa HS, Branco JM, Lourenço PB (2014) Characterization of cross sections from old chestnut beams weakened by decay. *International Journal of Architectural Heritage* 8(3):436-451.
- [25] Sousa HS, Sørensen JD, Kirkegaard PH, Branco JM, Lourenço PB (2013) On the use of NDT data for reliability-based assessment of existing timber structures. *Engineering Structures* 56:298-311.
- [26] Nowak TP, Jasieńko J, Hamrol-Bielecka K (2016) In situ assessment of structural timber using the resistance drilling method–Evaluation of usefulness. *Construction and Building Materials* 102:403-415
- [27] Tannert T, Anthony RW, Kasal B, Kloiber M, Piazza M, Riggio M, Yamaguchi N (2014) In situ assessment of structural timber using semi-destructive techniques. *Materials and structures*, 47(5):767-785.
- [28] Lechner T, Nowak T, Kliger R (2014) In situ assessment of the timber floor structure of the Skansen Lejonet fortification, Sweden. *Construction and Building Materials* 58:85-93.
- [29] Rinn F, Schweingruber FH, Schär E (1996) Resistograph and X-ray density charts of wood. Comparative evaluation of drill resistance profiles and X-ray density charts of different wood species. *Holzforschung-International Journal of the Biology, Chemistry, Physics and Technology of Wood*, 50(4):303-311.
- [30] Liao C, Zhang H, Wang X, Li D (2015) Condition assessment of wood structural members at Yu Tomb of the Ming Dynasty, China. *Materials and Structures*, 48(10) 3259-3267
- [31] Branco JM, Sousa HS, Tsakanika E (2017) Non-destructive assessment, full-scale load-carrying tests and local interventions on two historic timber collar roof trusses, *Engineering Structures*, 140:209-224.
- [32] Beer FP, Johnston ER, Dewolf JT, Mazurek DF (2012) *Mechanics of materials*. In McGraw-Hill (6th edn). New York, US.
- [33] Cabaleiro M, Riveiro B, Arias P, Caamaño JC (2015) Algorithm for beam deformation modeling from LiDAR data. *Measurement* 76:20-31.
- [34] Gonzalez-Jorge H, Riveiro B, Armesto J, Arias P (2012) Procedure to evaluate the accuracy of laser-scanning systems using a linear precision electro-mechanical actuator, *IET Sci. Meas. Technol.* 6(1):6–12.

Figures

Figure 1. Framework for the combination of laser scanner and drilling resistance tests for the assessment of the geometrical condition of irregular cross-sections of timber beams

Figure 2. Apparent area (A_L) obtained from laser scanner for measurements without visibility of the top surface and added area (A_H) corresponding to the data obtained from the drilling resistance tests.

Figure 3. Comparative diagrams of the improvements obtained in the calculation of the apparent section of timber beams by combining data obtained from the laser scanner and drilling resistance tests

Figure 4. Calculation of the residual cross-section (undecayed section) obtained from the data of the drilling resistance tests.

Figure 5. Timber specimen, with irregular cross-section and signs of deterioration by insect attack, used on the laboratory tests. The identification of the tested sections is indicated in the figure.

Figure 6. Laser scanning test (45° inclination scanning) with targets placed on the beam for the entry and exit points of the drilling resistance tests.

Figure 7. Schematic location of the beams and their cross-sections selected for analysis due to its level of deterioration (timber roof of Guimarães medieval castle keep)

Figure 8. Percentage of average error in the calculation of the apparent section regarding single tests or the combination of tests for the laboratory tests (45° inclination scanning), where I_x is the moment of inertia respect to the horizontal axis X , I_y is the moment of inertia respect to the horizontal axis Y , I_x principal is the moment of inertia respect to the principal axis X and I_y principal is the moment of inertia respect to the principal axis Y .

Figure 9. Percentage of average error in the calculation of the apparent section regarding single tests or the combination of tests for the laboratory tests (75° inclination scanning)

Figure 10. Percentage of average error in the calculation of the geometrical properties of the cross-sections from the timber beams from the keep of Guimarães Castle.