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DETERMINATION OF A WOOD DAMAGE ASSESSMENT SYSTEM BY MATHEMATICAL METHODS AND MINIMALLY INVASIVE MECHANICAL TESTS

Constantin Ștefan IONESCU
Transilvania University of Brașov, Faculty of Wood Engineering
Bulevardul Eroilor 29, 500036 Brașov, Romania
Phone number: 0040 741 485 550
E-mail: restaurareionescu@gmail.com

Aurel LUNGULEASA
Transilvania University of Brașov, Faculty of Wood Engineering
Bulevardul Eroilor 29, 500036 Brașov, Romania
E-mail: lunga@unitbv.ro

Cosmin SPÎRCHEZ
Transilvania University of Brașov, Faculty of Wood Engineering
Bulevardul Eroilor 29, 500036 Brașov, Romania
E-mail: cosmin.spirchez@unitbv.ro

Anamaria AVRAM
Laboratory of Restoration and Research "Restaurare Ionescu Constantin"
Henri Coandă 12, 550234 Sibiu, Romania
E-mail: avram.anamaria19@yahoo.com

Abstract:
This research aims to present methods for determining wood fragility as well as an original alternative method as a minimally invasive technical solution and the adaptation of a measuring device to determine damaged wood's hardness from cultural heritage. The high degree of novelty contributes to: 1. the adaptation and realization of a measuring device; 2. the elaboration of the method of measurement (for Mark 10 apparatus) of the hardness of the wood from the damaged works of art; 3. determining the hardness of degraded wood leads to accurate diagnosis; developing a hierarchy of levels of multi-stage deterioration of old wood allows the degree of intervention in the restoration of cultural goods to be assessed and provides the opportunity to evaluate the efficiency of consolidation treatment; 4. as far as we know, this type of determination is not used in any other laboratory by this date. We consider the development of this research to be innovative, and the authors argue that the proposed method is completely original. The conclusion of the paper highlights the strengths of the alternative methods researched, experimented and presented by us in order to determine the level of degradation of the wooden supports of the cultural heritage.

Key words: *hardness; porosity; wood; degradation; measurement.*

INTRODUCTION

Wood degradation can be defined as the loss of its attributes by the action of physiological-biological agents or by long-term use in an inappropriate environment, developed individually or cumulatively, and can be interpreted according to what causes it, by finding out the consequences and depending on the use of wood. Physico -chemical factors such as temperature, humidity, etc. may be the most harmful, causing chemical reactions, causing physical degradation of the wood (Moldoveanu 2010) and/or the installation and development of biological pests, micro, macromics, insects etc. Moisture (UR%) and temperature (T °C) are important factors both in terms of dimensional stability and insect development and activity. Mustaţă et al. (2013) show that normal insect activity occurs at temperatures between 5-40°C and that depending on the temperature, the ratio of their development is inversely proportional.

It is difficult to evaluate and develop a hierarchy of degradation levels, interpreted as natural defects or produced by endogenous or exogenous factors. The level of degradation practically expresses a degree of deterioration as a percentage of the initial value of a healthy wood.

The need to investigate and scientifically determine the parameters that determine the degree of wood damage (support for art objects) is due to the desire to save an artwork by establishing a correct diagnosis and, based on it, a restoration project and quantification with specific devices, the effectiveness of the treatment (Ionescu et al. 2019). An important element of the investigation is determining the level of loss of physical, chemical and mechanical properties of the wood which has suffered a severe biological attack (rot, xylophagic attack etc.), causing deterioration on the artistic creation which represents values of the national and/or world cultural heritage (Bedate et al. 2004).

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Particular attention should be paid to the mechanical properties of the wood, which, due to the additional porosity produced by xylophagus attack, loses its anatomical, mechanical strength and mass. Excessive porosity due to holes and insect galleries leads to excessive moisture absorption, which substantially changes the density and mechanical properties. With increasing humidity, the value of the flow limit decreases and that increases the size of deformations (Curtu and Ghelmeziu 1984). The mechanical properties of healthy and defective wood, such as elasticity or hardness, depend on many factors, such as anatomical features, apparent density, late wood percentage, natural porosity, etc. (Ionescu et al. 2019). Apparent density is interpreted by the ratio between mass and volume and the volume varies with the bound water content and the mass based on the total water content (Pescăruş 1978).

Wood hardness is one of the properties that can assess the degree of fragility and is understood as the opposition of wood to the penetration of a body, expressed by resistance to mechanical action that tends to modify its surface. There are several procedures to test the hardness of wood, but in the present paper we will refer to a conventional (commonly used) principle and to a process proposed by us.

In this study, we present two methods to determine the fragility of wood:

1. Determining the excessive porosity of wood caused by holes and insect galleries.
2. Comparative determination of the values obtained for healthy wood with the degradation by the Brinell method (standardized method) and that proposed by us, the XAAAL method, as a minimal destructive alternative.

OBJECTIVE

Obtaining methods for determining the fragility of wood, for heritage goods, and art objects with wooden support. Research, development and use of an original alternative device and method to determine the hardness of damaged wood in art objects showing lower destruction values inferior to the Brinell method.

MATERIAL, METHOD, EQUIPMENT

Healthy and/or degraded lime wood specimens (Tilia cordata Mill.) were used for this study. The samples had square sections (thicknesses) of 20x20mm and 50x50mm, with different lengths for Brinell and XAAAL tests. These were subjected to the two types of testing, i.e. Brinell hardness and XAAAL hardness (Fig.1). Measurements were made on three types of samples, degraded wood without treatment, new and healthy wood and wood with consolidation treatment, specific to the restoration field.

Fig. 1.
Determination (comparative) of puncture force (HX) and Brinell hardness (HB) on new, healthy wood sample.

Separately, hardness determinations were performed only with the XAAAL method, as well as determinations regarding the degradation caused by xylophagic attack, by the excessive porosity method, on degraded panels of several art objects in the restoration stages.

Method of determining excessive porosity

This work restrains the area of discussion of the biological factors harmful to wood from heritage objects, where we found the action of xylophage insects from the coleopteran family (the family Anobiidae) as the main degradation factor (Filipovici 1964) and the production of excessive porosity in art objects.

The evaluation of the degradation has been done so far by determining the number of openings per unit area, 1dm^2, with current values of 40-200 holes/1dm^2, being often specified by the majority of the researchers (Bucsa and Bucsa 2014); we consider that this approach is a simplistic one.

Our research brings an improvement in this respect, and extends the evaluation of the degradation produced by xylophagic attack, taking into account the diameter, surface and volume of the holes, this being determined by the fact that the diameter of the flight holes is variable, with significant differences between them. In order to obtain a consistent method, it is recommended first to take a visible and significant surface from the patrimony object, we recommend a square with the side of 10cm (area 100cm^2) (Fig. 2).

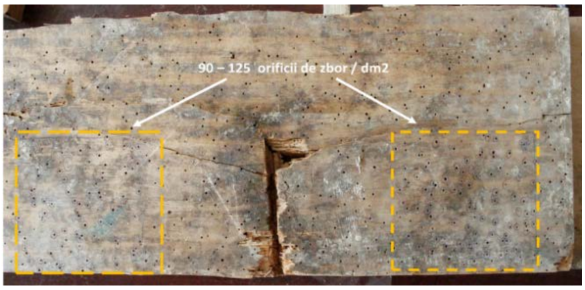


Fig. 2.
Marking and counting of the flight holes on dm^2.

On this known surface not only the number of flight holes is determined, but also an average diameter. In general, degradation intensity is determined as the ratio between the surface of the insect holes and the area taken into account. Considering the characteristics of the flight holes (number and average diameter), the Equation (1) is obtained. For a more accurate estimation, depending on the size of the panel, several reporting surfaces can be produced to reach a reference average for the entire panel.

$$P_e = \frac{A_o \cdot n}{l_1 \cdot l_2} \cdot 100\ [\%] \tag{1}$$

where:
P_e – excessive porosity expressed in %
A_o – hole flight area, determined with Equation (2).
n – number of holes on the whole surface (average);
l_1, l_2 – dimensional plane dimensions of the calculated area, in mm

$$A_o = \frac{\pi \cdot d^2}{4} \tag{2}$$

Since the equation (1) expresses a percentage of the orifices of the whole surface (that is, a percentage porosity), based on this, the volume of these holes in the wood support with the Equation (3) can be determined, which must then be filled with synthetic resins for consolidation (Paraloid B72, Regalrez 1126 etc.) during wood restoration operations.

$$V_g = A_o \cdot n \cdot V_p\ [m^3] \tag{3}$$

where we have:
V_g – void volume caused by the flight holes in m^3;
A_o – area of the flight opening
n – number of holes on the whole surface (average);
V_p – the volume of the wood floor, in m^3.

Determination of damaged wood hardness by the Brinell and XAAAL method

Brinell Hardness Testing (EN 1534-2000) consists of using a 10mm diameter steel ball that is pressed with a predetermined force of 100daN, maintaining pressures of approximately 25 ± 5 seconds. The remaining fingerprint has a certain diameter, which is measured as the arithmetic mean of two perpendicular diameters and, after obtaining its value, is calculated with relation (4), resulting in the Brinell HB hardness, in N/mm^2.

$$HB = \frac{2 \cdot F}{\pi \cdot D(D - \sqrt{D^2 - d^2})}\ [N/mm^2] \tag{4}$$

where:
HB – Brinell hardness (Newton per square millimeters)
F – the pre-selectable push force in newtons

π – is the „pi” factor ≈ 3,14
D – diameter of the ball (10 mm)
d – diameter of the residual indentation

The Brinell method for determining and assessing the hardness of the wood (healthy or damaged) is an invasive and destructive process even if the small fingerprint is about 4-8mm in diameter and 1-2.5mm in depth. Although these traces are very small and testing can be done on the back of the patrimony object, we argue that the Brinell method destroys part of the outer surface of heritage objects, and this is undesirable. Moreover, this test method is disadvantageous in that the stand is fixed and robust, being suitable for testing small dimensional samples; the inconvenience of its use in restoration is the impossibility of extracting test specimens from the cultural good. It should be noted that the polychrome panels vary dimensionally and in shape, and the distribution of the degradations is not constant (Ionescu et al. 2019).

The XAAAL Test Method (with Mark 10) is based on the penetration into the wood of a cylindrical body with a conical tip with a diameter of 1.34mm and a length of 6mm (Fig. 3), with a pushing force indicated on the digital screen of dynamometer, expressed in [N].

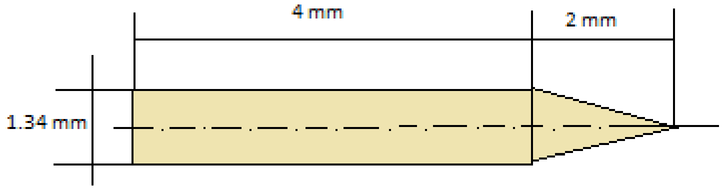


Fig. 3.
The shape and size of the Mark 10 penetrator.

The calculation formula designed by the authors with relation (5) determines the total lateral surface or the surface of the remaining hole in the wood resulting from the penetration of the tip, and the puncture resistance (hereinafter referred to as "XAAAL hardness" (HX) is determined as the ratio of the force puncture and total penetrating area (Ionescu et al. 2019).

$$HX = \frac{2 \cdot F}{A_l} \, [N/mm^2] \tag{5}$$

where:
HX – hardness marking in N/mm^2
F – The force read on the Mark 10 dynamometer, in N
A_l – the total lateral surface of the peak penetrator, determined as a sum of the cylindrical and conical part (21,28 mm^2).

The Mark-10 (M3-200) digital machine measures forces in N in a range of 0-1000 N, and is designed to test compression and traction for various applications (including wood support) using tips of various shapes (Fig. 4).

The device consists of: stand with columns, rack, centering and fixing plate, drive lever, dynamometer, and penetrator (puncture tip).

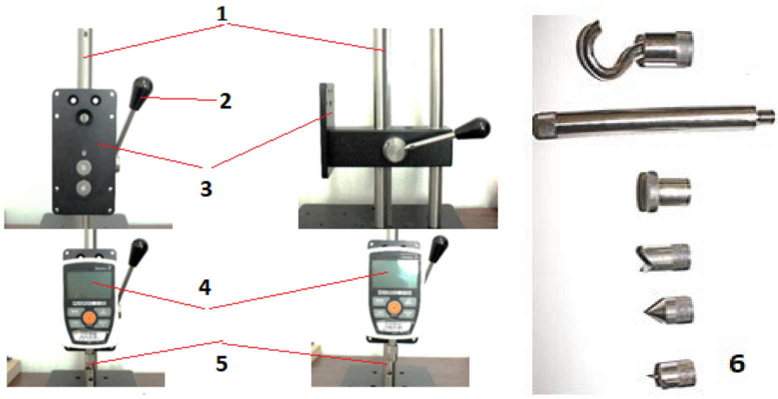


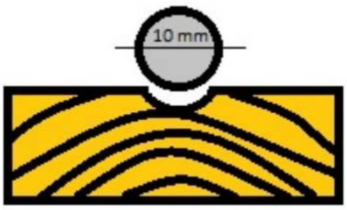
Fig. 4.
Device with dynamometer Mark 10: 1 - dynamometer displacement columns; 2 - drive lever; 3 - dynamometer support plate; 4 - dynamometer; 5 - fingertip dial; 6 - current compression and traction peaks of the dynamometer.

The degree of brittleness (F_d) of wood is determined by measuring the HX hardness with the Mark 10 device as a percentage of the loss of degraded wood properties compared to the initial value of healthy wood. In this respect, the authors formulated the calculation Equation (6).

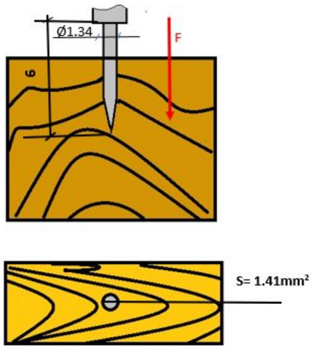
$$F_d = \frac{HX_s - HX_d}{HX_s} \cdot 100\ [\%] \tag{6}$$

where:
F_d - is the degree of fragility in %;
HX_s - the wood hardness determined with Mark 10 in N/mm^2
HX_d - the hardness of the damaged wood determined by Mark 10 in N/mm^2

As for the method of measuring the hardness, one cannot speak of novelty, but our research brings an original contribution by the alternative of adapting and using a versatile device (Mark 10) and a method of calculating the force required for the penetration of a steel tip with a diameter of 1.34mm in a wooden panel. Comparison of compression or traction forces indicates the deterioration of wood panels that have reached various degrees of degradation due to multiple reasons: aging of the material, loss of anatomical elements of the wood as well as physical and mechanical properties or biological attack and xylophages). Fig. 5 graphically presents the imprint of the two types of penetration and the difference in destruction. (Ionescu et al. 2019)



a.



b.

Fig. 5.
Graphic examples of standard hardness print types
a. print type for Brinell hardness; b. XAAAL hardness, type print.

RESULTS AND DISCUSSION

The number of holes and their diameter (ø 1,4 ÷ 3,6mm) influence the resistance of the wood and increases the degree of fragility. According to Table 1, a xylophage attack of more than 100 holes/dm^2, with 2.5mm apertures reduces resistance to 60%.

Table 1

Influence of the number of flight holes (mean 2.5mm) on the XAAAL hardness

Number of holes/dm^2	Penetrating force medium values [N]	Resistance reduction %	XAAAL hardness [N/mm^2]
0-15	210	≤ 2	19.73
20-25	168	16	15.78
30-50	132	34	12.40
70-100	87	66	8.17
142-170	26	87	2.44
≫200	7	≥97	0.65

We wanted to correlate the results obtained by using the XAAAL method with one of the standardized procedures (presented in this study), namely the Brinell method, as an accepted method. Our proposal wanted to provide similar answers, according to Table 2, but with lower destruction than the benchmark.

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For this study 30 specimens were tested. Other 30 values were obtained in determining the assessment of degraded wood.

Table 2

Mark and Brinell hardness, on two types of samples, new and healthy wood and degraded wood

Epruv.	No.	HB, N/mm^2	HM, N/mm^2	Fragility degree, %	
				of HB	of HM
TD4, New and un-treated wood	1	18.36	19.07	0 (neutral)	0 (neutral)
	2	17.35	17.95	0 (neutral)	0 (neutral)
	3	15.11	13.43	0 (neutral)	0 (neutral)
	4	17.45	17.00	0 (neutral)	0 (neutral)
	5	16.95	16.62	0 (neutral)	0 (neutral)
	Medium	17.20	16.81	0 (neutral)	0 (neutral)
TD9, Degraded and un-treated wood	1	4.14	2.91	77.4	84.7
	2	4.56	3.85	73.7	78.5
	3	5.30	7.51	64.9	44.0
	4	4.46	4.85	74.4	71.4
	5	4.76	4.65	71.9	72.0
	Medium	4.66	4.75	72.9	71.7

Thus, we can correlate the degree of fragility in Table 2 with Table 1, where we can deduce the level of flight holes. For example, a frailty of 72% is equivalent to a xylophage attack intensity of 100 ÷ 142 holes/dm^2.

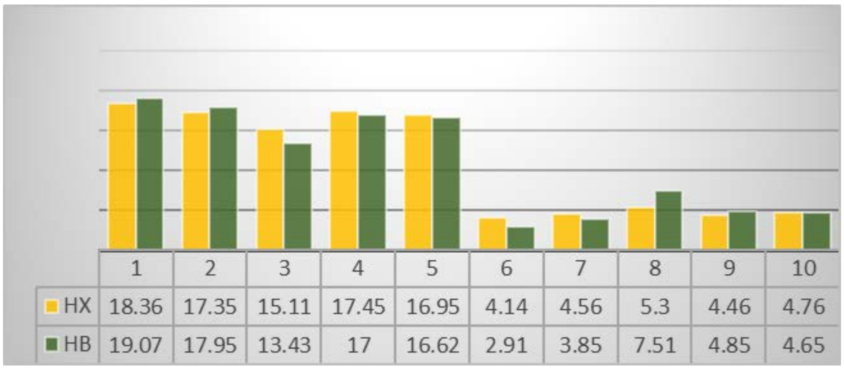

Fig. 6.
Comparative graphical representation of XAAAL and Brinell hardness.

CONCLUSIONS

The increased number of flight holes/dm^2 reduces the penetration resistance of the tip. In this respect, more than 60 flight holes/dm^2 reduce the puncture resistance (in the case of the XAAAL method) to 110N; at more than 100 holes/dm^2, the resistance drops to 40N and at more than 220 holes/dm^2, the force is reduced below 10N.

Correlation of the Brinell hardness measurement results with the wood resistance measured with the MARK 10 test bench starts from the premise that puncture degradation is a less destructive method than the Brinell method.

The original methods presented may offer advantages in the field of polychrome wood restoration. Thus, the method of determining excessive porosity (PE) is beneficial for determining the level of damage of a wooden panel. From the principle of this method, a calculation model has been developed for the need for the consolidation solution needed for that degraded panel.

The XAAAL hardness determination method - in addition to determining the degree of damage - can also determine the efficiency of the consolidation treatment the panel has been subjected to.

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