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THE EFFECT OF NATURAL AGEING ON THE PROPERTIES OF OAK WOOD FROM NOTRE-DAME-DE-PARIS CATHEDRAL

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ABSTRACT: The fire at Notre-Dame Cathedral in Paris (NDP) was a disaster that nevertheless led to several scientific breakthroughs. The remains of the roof frame constitute a large stock of oak wood dating from the 12th to the 19th century, offering a rare opportunity to study the ageing properties of wood. Following several research initiatives, the results presented here aimed in particular at 1- consolidating matching techniques to compare old and recent wood, 2- determining hygroscopic behaviour, 3- assessing instantaneous elastic properties. The disturbance depth of the fire was assessed using spectrocolorimetry analysis. Fiber saturation point and transverse surface shrinkage coefficient were measured. And finally, preliminary 3-points bending tests performed on a small number of samples from the 12th to 19th century highlighted the considerable variability of such material. Particular attention must be paid to the composition of the experimental groups to be set up to assess the ageing of the wood.

KEYWORDS: Oak, Aging, Matching, Mechanical behaviour, Hygroscopicity, Reuse

1 – INTRODUCTION

Knowledge of the properties of old wood is necessary for the decision-making of engineers faced with the replacement of structural elements resulting from the deconstruction of old buildings or the maintenance of a historic monument. Research carried out in Japan using wood salvaged from traditional buildings [1] has highlighted several trends in the effect of natural ageing: degradation of polysaccharides, darkening [2], little effect on stiffness or even strength, decrease in fracture energy, especially in the direction transverse to the grain [3].

Such research comes up against two major difficulties: obtaining a well-identified sample of old wood and the intrinsic variability of the material. The ageing in question here is the slow oxidation in volume, independently of the additional effect of surface degradation (weathering) or mechanical damage induced by mechanical or hygromechanical actions.

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In the case of Notre-Dame Cathedral wood, the effect of fire should also be considered, resulting in the presence of a charred wood envelope around the remains of the beams, and, under this envelope, of 'torrefied' wood modified by heat in addition to age. In this paper, preliminary observations made of some physical and mechanical properties will be presented and discussed.

The first results concern the anatomical description of the samples, qualification by spectrocolorimetry to assess the depth of carbonization, measurement of fiber saturation point and swelling coefficient, and determination of the instantaneous mechanical behaviour in 3-point bending apparatus, providing elastic modulus and bending strength.

2 - PROJECT DESCRIPTION

The current project, funded by CNRS (French Scientific National Research Centre) aims to characterize how the mechanical and hygroscopic properties of oak wood change with age. Led by Institut Pascal (France), it also involves other laboratories in France, Japan and Italy. Samples of NDP-referenced beams were cut and distributed among the various teams.

3 – PREPARATION OF SAMPLES

Beams issued from the fire of Notre-Dame de Paris were partially burnt and contaminated with lead from the melting of the roof. For each supply of new beams, the charcoal layer had to be be removed. The blocks were machined in a radial direction, with a thickness of 30 mm. This choice allowed us to situate ourselves in relation to the pith, whenever possible. The partially charred beams varied widely in geometry, Figure 1. The blocks were machined in a radial direction, with a thickness of 30 mm. The samples required for the various experimental campaigns were taken from these geometries. In addition, crosscuts 2-3cm thick had been cut from some blocks for global observation of wood appearance.

Indications in date used in this paper come from CASIMODO ANR Project, in progress. date of tree felling is retained here. Three batches of ancient wood were chosen, and referred with following codes:

- XIIe: trees felt at the end of XIIth century
- XIIIe: trees felt at the beginning of XIIIth century, present at the origin of building,
- XIXe: Trees felt during XIXth century, providing from the cathedral's spire built by Viollet le Duc.

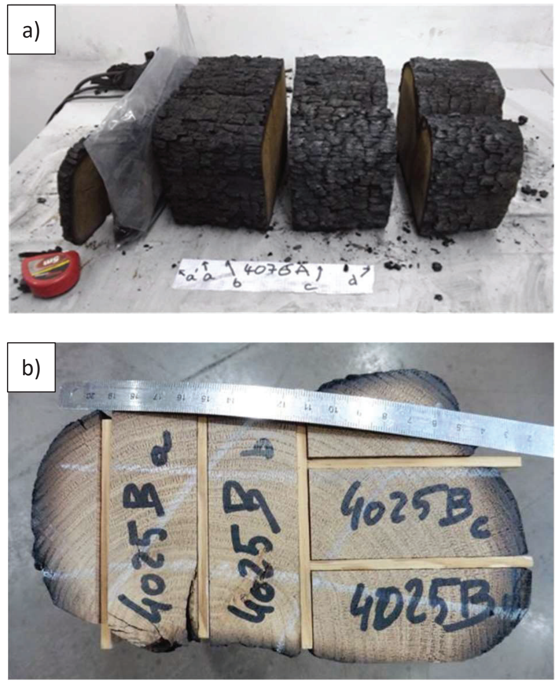

Figure 1. Preparation of samples: a) Raw appearance of beams and pre-cutting, b) cutting in radial samples

4 – FIRE PERTURBATION

The colour changes that wood undergoes as it ages are a general decrease in lightness and saturation. These changes are similar to those observed in heat-treated wood, fig.2 [2].

4.1 MATERIAL AND METHOD

Spectrocolorimetry measurements were obtained on crosscuts from all centuries, and given in the CIELab reference space [5].

4.2 RESULTS

The L^*, a^* and b^* values show similar variations according to position.

The effects of fire are limited to exterior part of beams, and internal one is referred as "intact" wood, supposed only affected by time effects, Figure 2a,b. All samples used in the following sections are issued from intact parts.

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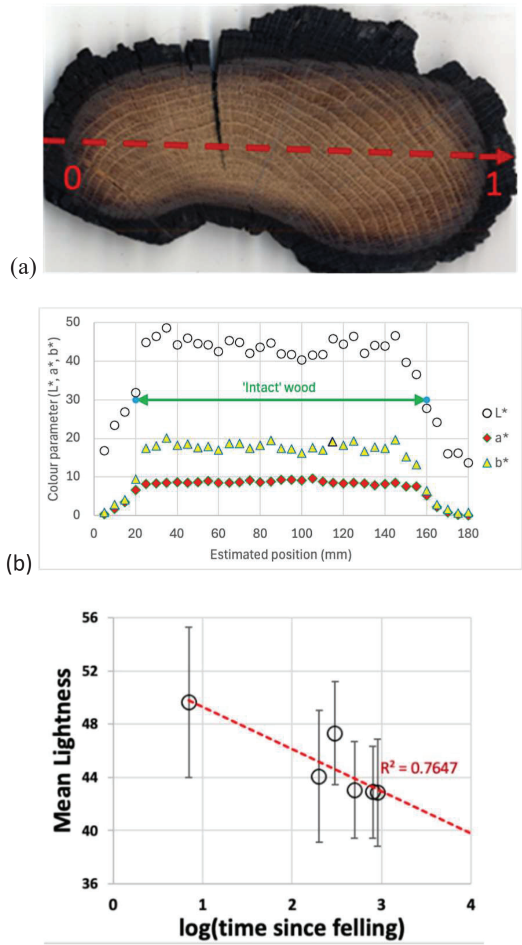

*Figure 2. Measurement of colour parameters: (a) Crosscut 4025_B (XIIth century); (b) profile of colour parameters; (c) Effect of age on lightness L**

Fig 2c shows the relation between the lightness L^* and the time since the estimated tree felling. It confirms the previously observed trend [2].

5 – HYDRIC BEHAVIOUR

As a modification due to oxidation of hemicellulose is assumed, the aim of this part is to evaluate potential disturbance of hydric behaviour of ancient wood. Two parameters in particular are targeted here : determination of fibre saturation point (FSP), and shrinkage coefficient either in the radial direction (RS) or the tangential direction (TS).

5.1 MATERIAL AND METHOD

The procedure of CIRAD described in [6] is applied. The required geometry is 10 mm in L, and 20 mm in R and T directions, Fig. 3. Samples A, B, C and D were dated from XIIth century. Samples F and J were undated, but probably from XIIth or XIIIth century. Samples A, B, C came from the same beam, and samples D and E too. Samples were initially water saturated and successively stabilized according to conditions described in Table 1. Mass, radial and tangential dimensions were measured at each step. Measurement of the saturated volume of the specimen (by Archimedes' thrust) during the saturated step made it possible to simultaneously obtain basic density. The expected equilibrium moisture content (EMC) was also defined, according to CIRAD procedure [6]. According to [7], expected technological characteristics for European oak are summarized in Table 2.

Table 1 Stabilization step and expected moisture content

	Temperature (°C)	Relative Humidity (%)	Expected EMC CIRAD (%)
Step 1	30	85	18
Step 2	20	65	12
Step 3	20	30	6
Final step	103	-	0

Table 2 Expected technological characteristics for recent oak [7]

Property	Mean value
Density at 12%	740 kg/m^3
Total Tangential Shrinkage coefficient (TS)	9.7 %
Total Radial Shrinkage coefficient (RS)	4.5 %
Fiber Saturation Point (FSP)	31 %

Figure 3. Samples for hydric tests

5.2 RESULTS

Measured moisture content values are presented in Table 3. Dispersion of moisture content values was low, particularly when repetitions in beams are compared. The measurement procedure was then confirmed as very stable and repetitive. EMC mean values of steps 2 and 3 were close to expected ones, but values of step 1 were lower than expected.

Measured technological characteristics for ancient wood are summarized in Table 3. Mean values were very similar to characteristics of recent wood, for an equivalent density, Table 4. At this point, no clear influence of ageing on oak wood could be observed.

However, a significant dispersion of value was observed. These differences could be correlated with slight variations in the anatomy of the samples. Oaks present big vessels in the initial wood of the annual ring, and are classified in the group of ring-porous woods. In favourable growing conditions, a large annual ring is then mostly constituted of final wood, higher in density. A very good fitting can be observed between measured hydric characteristics (FSP, TS, RS) and ring width, Fig. 4. For the three characteristics, a very accurate repetition of data can be observed, to such an extent that the points were superimposed. Correlation coefficients for a linear regression connecting to ring width were the following:

- $R^2 = 0.93$ for FSP
- $R^2 = 0.81$ for TS
- $R^2 = 0.91$ for RS

Growth ring width is confirmed as an essential parameter to quantify wood in general, and oak properties in particular.

Table 3 Equilibrium moisture content values, density and ring width

	EMC step 1 (%)	EMC step 2 (%)	EMC step 3 (%)	Density Step 2 (kg/m^3)	Ring width (mm)
A2-1	13,73	11,67	6,56	666	1,6
A2-2	13,78	11,62	6,54	656	1,6
B1-1	14,79	12,49	6,85	732	2
B1-2	14,65	12,43	6,82	734	2
C1-1	15,04	12,74	7,00	745	1,8
C1-2	14,90	12,69	6,95	742	1,8
D2-1	16,26	13,93	7,47	738	3,9
D2-2	16,20	13,85	7,41	739	3,9
E1-1	16,03	13,68	7,38	790	5
E1-2	15,92	13,63	7,42	798	5
F1-1	15,28	12,95	7,02	648	2,2
F1-2	15,34	13,03	6,97	642	2,2
J1-1	15,69	13,35	7,02	688	2,9
J1-2	15,69	13,20	6,95	699	2,9
Mean value	***15.24***	***12.95***	***7.03***	***715***	
σ	*0.81*	*0.73*	*0.30*	*50*	
COV	*5*	*6*	*4*	*7*	

Table 4 : Measured technological characteristics for ancient oak

Property	Mean value	Stand. Dev.	COV (%)
Density at 12%	715 kg/m^3	50 kg/m^3	7
Total Tangential Shrinkage coef. (TS)	9.94 %	2.51 %	25
Total Radial Shrinkage coef. (RS)	5.32 %	1.66 %	31
Saturation Point Fiber (SPF)	30.7 %	6.51 %	21

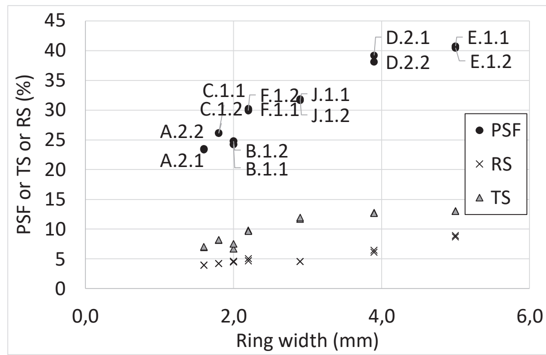

Figure 4. Evolution of Saturation Point Fiber, Radial Shrinkage and Tangential Shrinkage according to annual ring width.

5 – MECHANICAL BEHAVIOUR

5.1 MATERIAL AND METHOD

In [5], quasi-static mechanical tests were led with a 3-point bending procedure. The geometry of samples was 120 mm long in L direction, 20 mm wide in R direction, and 5 mm high in T direction, direction of loading. Tests were carried out until failure. The modulus of elasticity (MOE) and the maximal bending strength (MOR) were then available.

The contemporary oak was mainly obtained from two sources, one from the Nancy forest (Noted XXI-a) and another from the Beltranges forest (noted XXI-b), France. Unfortunately, the choice of individuals was made before access to old oak was possible, so no parameters of matching, particularly anatomical similarity, were used at this time. The number of ancient wood samples is 165. Dates are divided between XIIth, XIIIth and XIXth centuries. 193 samples were prepared from trees felled in XXIth century.

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5.2 RESULTS

The bending test for aged wood was performed after the conditioning at 20 °C and 65% RH. Density values are presented in Table 5. Trees chosen in the XIIth and XIIIth centuries were quite similar, and also close to the reference proposed in [7], see Table 6. Trees chosen for the restoration of the XIXth century appear significantly lighter. Recent oak samples available in this study were denser than ancient wood samples. If samples coming from Beltranges forest (XXI-b) were actually quite close to the reference, specimens from Nancy forest (XXI-a) were noticeably heavier. Nevertheless, for every batch of samples, dispersion was quite low.

Table 5 : Density for each date and 35%RH – 20°C conditioning.

Property	Century	Mean value (kg/m^3)	Stand. Dev.	COV (%)
Density	XIIe	716	36	5%
	XIIIe	734	32	4%
	XIXe	643	32	5%
	XXIe-a	815	13	2%
	XXIe-b	769	33	4%

Elastic modulus and bending strength values at 12% moisture are presented in Table 6. Unfortunately, the bending test results for recent wood are not yet available. Compared to the reference for recent wood, and for an equivalent density, the elastic modulus (MOE) is lower for ancient wood samples. If trees from XIIth and XIIth centuries chosen at the origin of the building of the cathedral show very similar elastic modulus values, wood from XIXth century once again stands out with lower value. We can note, but without explanation to propose, that the dispersion of values is low for the XIIIth century batch, and rather high for the XIIth century one.

For bending strength values, almost the same conclusions can be drawn, except that values from XIIth and XIIIth centuries are equivalent to recent one.

Dispersion of relation between density and elastic modulus and bending strength are presented respectively in Figure 5-a) and Figure 5-b). In both cases, the important dispersion in XIIth century batch disturb a relation which appears overall linear. Nevertheless, this global linear tendency very well includes the value proposed as a reference for recent wood.

Table 6 : Elastic modulus and bending strength at 12% for each date, and for TROPIX data for recent oak [7]

Property	Century	Mean value (MPa)	Stand. Dev.	COV (%)
MOE	XIIe	11 876	1 913	16 %
	XIIIe	11 647	855	7 %
	XIXe	8 636	890	10 %
	Ref. CIRAD	13 300	-	-
MOR	XIIe	91	21	23 %
	XIIIe	108	9	8 %
	XIXe	82	10	13 %
	Ref. CIRAD	105	-	-

To minimize the effect of dispersion of XIIth century batch, particularly due to weak values as well as of elastic modulus and bending strength, the relation between these two characteristics is presented in Figure 6. The representation obtained, globally linear as expected, suggests that a part of the XIIth century batch presents damaged mechanical behaviour despites a high value of density. It is, however, impossible to assign this potential damage to ageing or to the fire and the collapse of the roof structure of the cathedral.

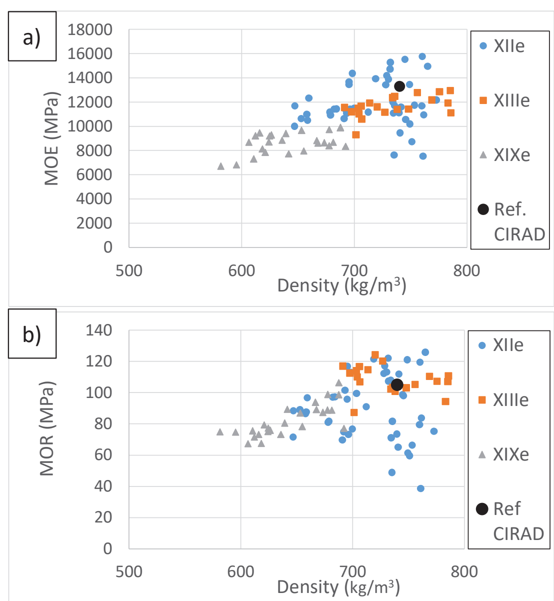

Figure 5. Relation between density and a) elastic modulus (MOE), b) bending strength (MOR).

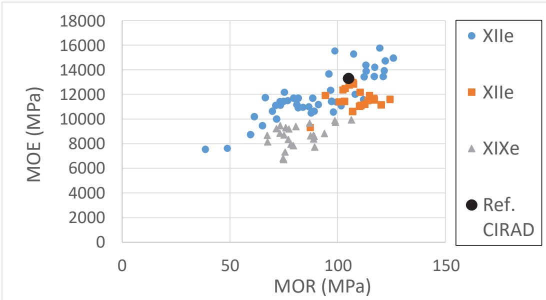

Figure 6. Relation between) elastic modulus (MOE) and bending strength (MOR)

As observed in the previous paragraph, the ring width is a strong marker of anatomy of oak, and has a very significant influence on hydric behaviour. As a way of thinking to propose a better understanding of mechanical behaviour of oak according to anatomical properties, elastic modulus and bending strength are presented as a function of ring width in Figure 7.

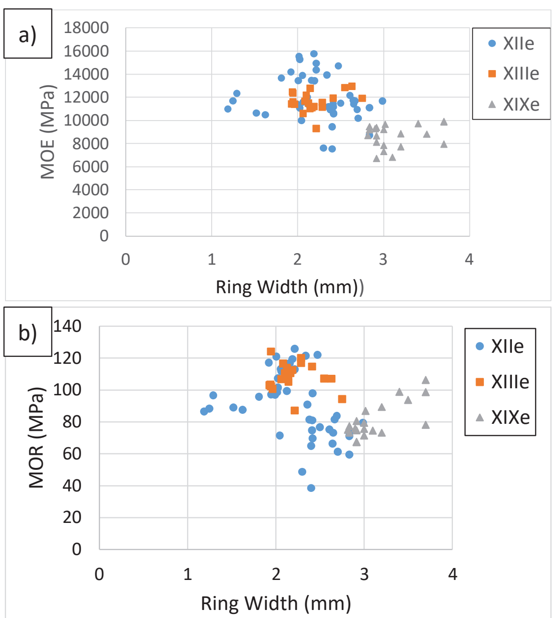

Figure 7. Relation according to ring width of a) elastic modulus (MOE), b) bending strength (MOR).

Finally, the relation between two anatomical properties, density and ring width, is proposed in Figure 8. Again, it can be concluded that wood properties of XIIth and XIIIth centuries are close, and the ones chosen in XIXth century are different. The dispersion of the two batches of recent wood of XXIth shows a significant difference: samples providing from Nancy (XXIth-a) were quite homogeneous, and could be correlated to woods from XIIth and XIIIth; in contrast, samples from Beltranges (XXIth-b) suggested a different anatomy, with high values of density for ring width varying between 1 and 5 mm.

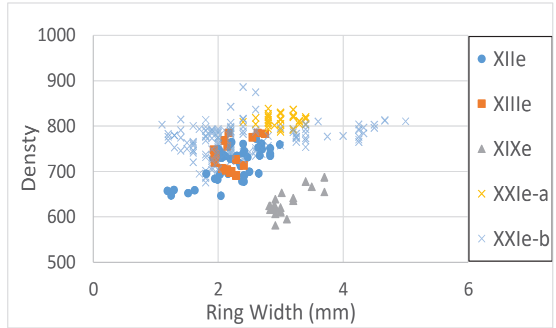

Figure 8. Relation between density and ring width for ancient wood and 2 batches of recent wood.

6 – CONCLUSION

The main conclusions of the study are listed below:

- The heat of the fire of the cathedral has torrefied the wood in a small depth under the charcoal layer. This depth was estimated at 2 cm thanks to spectrocolorimetry results.
- Hydric tests from saturation to anhydrous state provided an estimate of the fibre saturation point through measurement of transversal surface shrinkage. No significant difference of mean values could be observed between ancient and recent wood. However, this study highlighted the huge dispersion of results, and their dependence to the ring width.
- Bending test on small samples shows, as expected, a relation between density and mechanical properties. The results do not allow us to identify of eventual ageing. The large dispersion of values for XIIth samples makes it impossible to distinguish between the effect of ageing and potential damage due to the collapse of the roof.

Dependence to anatomical constitution, in particular ring width, is very strong. In order to consolidate methodology on study of ancient wood, a pair matching to evaluate an eventual influence of ageing on hydric or mechanical behaviour must necessarily and carefully consider equivalence's parameters of sample's anatomy.

In prospects, the mechanical tests should be consolidated with results on XXIth century samples. And finally, if defect-free samples do not present significative behaviour due to ageing, studies need to be carried out at the lumber scale. At this scale, macroscopic defects as cracks may have an influence. Different methodology has to be used, especially non-destructive techniques, in

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order to strengthen our knowledge of risks due to evaluation of ancient wood and re-employment.

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8 – REFERENCES

[1] Kohara J. (1958) Study on the old timber, Res. Report Fac. Engin., Chiba University 9 (15):1-55

[2] Matsuo M., Yokoyama M., Umemura K., Sugiyama J., Kawai S., Gril J., Kubodera S., Mitsutani T., Ozaki H., Sakamoto M., Imamura M. (2011) Aging of wood: Analysis of color changes during natural aging and heat treatment, Holzforschung 65(3):361-8.

[3] Yokoyama M., Gril J., Matsuo M., Yano H., Sugiyama J., Clair B., Kubodera S., Mistutani T., Sakamoto M., Ozaki H., Imamura M., Kawai S. (2009) Mechanical characteristics of aged Hinoki wood from Japanese historical buildings, C.R. Physiques 10(7):601-11

[4] Kranitz K., Sonderegger W., Bues C.T., Niemz P. (2016) Effects of aging on wood : a literature review, Wood Sci. Technol. 50(1):7-22.

[5] Bourchanin M. (2023) Effect of time heat and fire on the properties of oak, Internship report, Wood Sciences Master, Montpellier, France.

[6] Guibal D., Gerard J., Guyot A. (2023) Method of calculating the FSP (Fibre Saturation Point) from the variation in surface area of the radial-tangential plane, 12th symposium of GDR 3544 « Wood Sciences » Limoges, France.

[7] TROPIX 7 database, CIRAD, https://tropix.cirad.fr/