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Oak beams in medieval frameworks: constraints and advantages for restoration.

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Highlights:

- Wood is always a top material for beams
- 40 million of slender young oak trees are available in French forest
- Round-wood squared at the minimum keeps the high resistance of trunks
- Using green wood is the fastest and most energy-saving method
- High tech modern techniques can be used for the best sorting of trees

Abstract:

During the fire of Notre-Dame de Paris, all timber frames coming from the Middle ages period, in the nave and choir, were burnt. It was decided to proceed as possible to an identical reconstruction, but many questions arise about the timber frame. Is wood outdated as a material for beams? Is oak wood the best solution for timber frame? Are we able to find similar long slender oak beams in today French forest? Is it safe to use green wood for the building?

In fact, the forested area in France is the same today as in the Middle ages period, but two times higher than during the 19th century. Results from the forest inventory proves that 40 million slender oak trees are available in order to sort around 1500 trees for the restoration.

Cathedral heritage provided a demonstration of the high efficiency of carpenter's know-how. Most of oak beams kept their functionality for more than 800 years. This is a nice experimental result for a very long mechanical testing. Wood, emerged as material 300 million years ago as a result of long time evolution, is used to build trees, which are a collection of wooden beams able to resist flexure forces, for a long time.

Technical know-how about timber frame is old in human societies and was improved during the Middle ages, but scientific knowledge about wood as an anisotropic material is very recent. The background in mechanics for such material has been developed in early 20th century and observation tools for material structures at the nanometre scale appeared in late 20th century. Wood can be considered as an archetypal high-tech material using polymer-with-additive technology combined to nanostructured fibre-composite within a honeycomb-like micro-structured material. This explains why nature solution for tree beams is very efficient in terms of bending resistance per weight.

The mechanical behaviour of wooden beams is highly sensitive to the orientation of the main direction of anisotropy (grain direction) relative to bending forces. Natural beams in trees are built by a kind of 3D printing process so that grain orientation at beam periphery is always optimum. Mechanical bending performance of these beams (round-wood), in spite of branching, is equivalent to the performance of standard clear-wood specimens documented in databases. Squaring at the minimum this round-wood should be done while keeping grain angle closest to zero-degree value, which is performed by specific axe-hewn log squaring. The result

is “coarse” slightly curved beams much more resistant than “nicely” straight sawn beams with local grain angle above 10°.

Using directly green wood in the building process is effective for time of building and energy consumption. The drying of wood induces long deep longitudinal cracks and a reduction in beam section but a bigger increase in wood mechanical performance. If the green frame resists, the dried one will resist all the following years.

Finally, today carpenters have kept the building know-how and there are many modern non-destructive techniques available for the best sorting of trees and mechanical evaluation of beams.

Keywords:

Notre-Dame de Paris - Timber - Oak - Green wood - Restoration

1. Introduction

In April 2019 Notre-Dame de Paris was partially destroyed by fire. In particular, all wooden beams of the nave and choir timber frames dating from the Middle ages as well as spire timber frame dating from nineteenth century have been burnt. Following the destruction of Notre-Dame frameworks, three alternative solutions for restoration (identical, idealized or free-inspired) presented by the chief architects were discussed in a meeting of the National architecture and heritage commission, in march 2021. The commission vote in favour of identical reconstruction, chosen for its respect of Venice chart, the ability to attest and transfer carpenter’s know-how and the information about history of the cathedral building. Final decision was taken by the highest French authority.

Indeed, roughly half of these beams were still serving their required mechanical function since 800 years, half since 160 years. Moreover, wood material may be considered, as the sole material, apart from stone, to allow so long durability in building construction. But using material issued from forest trees raised questions about what is “identical” in the reconstruction process, what do we know about oak trees in the Middle ages forest and about artisanal knowledge and know-how 800 years ago in France? Here, we mainly focus on the selection and use of the long oak beams for the reconstruction of the Middle ages frame of Notre-Dame.

In the section 2, we propose a state of art on the evolution of French forest evolution, the technological knowledge in civil engineering and the scientific knowledge on wood. Section 3 deals with the mechanical characteristics of squared timber beams. In section 4, the use of oak species is justified for cathedral timber frame and section 5 analyses the impact of green wood use for the construction phase. Finally, the use of today’s techniques and knowledge is quickly discussed in section 6 in order to assist the restoration of Notre-Dame.

2. Major evolution in the French forest area and on technological and scientific knowledge

2.1. French forest evolution

We have a rather good estimation of forest area within hexagonal France territory (excluding overseas departments) during the last millennium [1,2]. In the 12th century, when the Middle ages timber frame of Notre-Dame was built, total forest area was very similar to 21st century situation: around 16 million hectares (Fig. 1). But between these two periods there was first a strong decline down to 7 million hectares at the beginning of the 19th century, when Viollet-le-Duc built the spire. Colbert issued a government decree on forest management in 1669 in order

to restore wood production imposing severe restriction to tree felling and higher harvest age (> 150 years) for timber use.

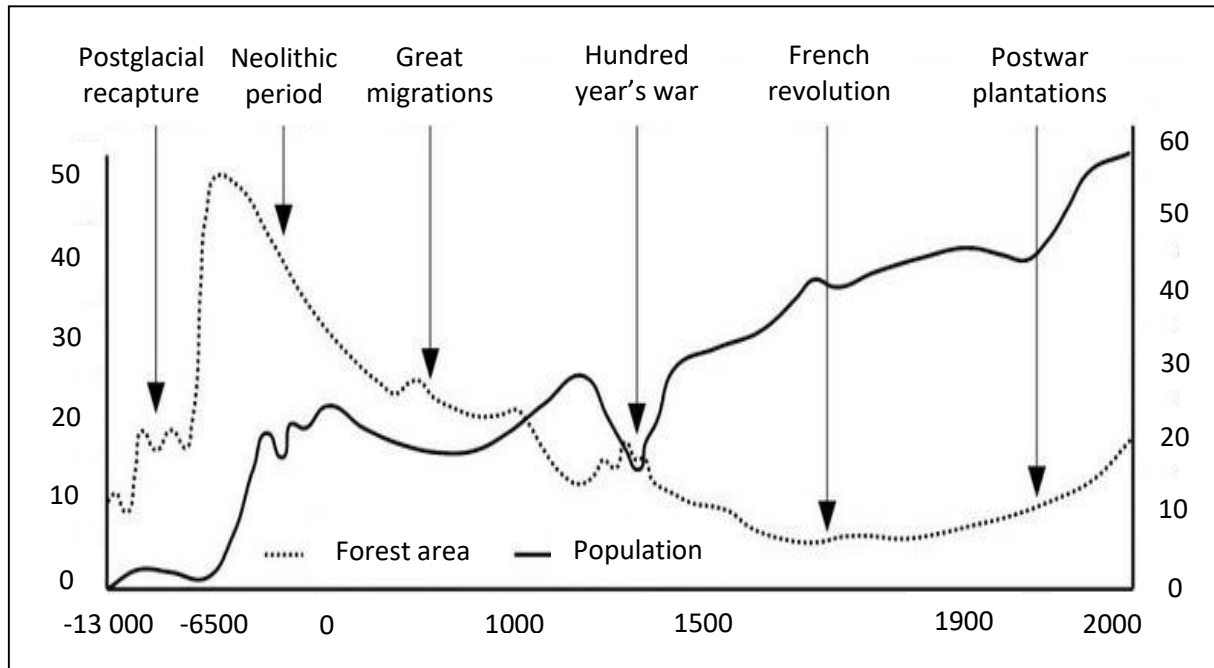


Fig 1. French forest area (million ha) and population (million people) in the last 15000 years (From Escurrat 1995 [2])

The diocese of Paris was the owner of oak forests where Maurice de Sully, bishop of Paris at the beginning of Notre-Dame construction could harvest some 1300 trees converted into beams for the choir and nave timber frame. From dendrochronological studies [3,4] on Notre-Dame beams and other cathedrals built in the same period, it is well documented that selected oak trees were young (50 – 100 years old) and slender trees (ratio between total height and diameter above 70), with a small diameter at breast height (25 – 40 cm). This was a deliberate decision because there were plenty of old (200 years old) big (60 cm diameter or more) oak trees available at that period. But it is not clear whether these trees come from young high forests or old coppices. The long, straight, and slender beams used in the frame were nearly crude trunks with pith at the centre, just squared, keeping the local small curves if needed.

For Viollet-le-Duc, for the construction of the spire timber frame, the situation was totally different. Oak trees available for harvest should be old enough by forest legislation and they were big trees coming from mature high forests. The long, perfectly straight slender beams were sawn.

Today French forest is always very rich in oak trees, both in high forests and coppices which are sometimes rather old. Looking in the data from the national French forest inventory (IFN) there are 44 million oak trees for the Middle ages category needed for the restoration of Notre-Dame (Table 1). There is a large place for a good choice but the question is: what was a good choice by the carpenter in the Middle ages forest?

Table 1 Number of available oak trees in French forest

Diameter class	Total trees	Height	Slenderness
cm	M trees	m	-
22.5 to 27.5	14	24 to 31	90 to 130

27.5 to 32.5	14	25 to 37	80 to 30
32.5 to 37.5	16	26 to 33	70 to 100
Total	44	24 to 37	70 to 130

Present data from National forest inventory (IFN), <https://inventaire-forestier.ign.fr/>

M trees: number of trees in million trees

Height: total height of the tree

Slenderness = Height / Diameter

Total small: trees for Middle–Age reconstruction

Total big: trees for 19th reconstruction

2.2. Technological knowledge in civil engineering

Woody parts of a tree like trunks are slender beams resisting to compression and bending efforts, just like beams in a timber frame. In fact, inspiration from nature was an obvious and easy solution. Timber frame using round wood (eventually squared) is a very old and universal building method before the Middle ages period of Notre-Dame [5,6] and the transfer of technological know-how was done by carpenters themselves. There were surely many innovations in the field of connexions for example, and an increase of knowledge about construction and wood material during the very rich period of cathedral building in the Middle ages. But it is not well documented, apart from wooden heritage where scientific investigation could try to identify the main innovations that occurs.

The scientific revolution, with documented technological processes and basic knowledge (mechanics of materials and structure for example) comes in the late 18th century [7,8]. When Viollet-le-Duc built the spire of Notre-Dame, basics in mechanics and civil engineering (including timber frames) were taught by Navier [7]. More or less, the same basics are always behind timber engineering today.

In Europe, since 2004, standard rules for timber building conception are in use under the title: Eurocode 5: Design of timber structures [9]. They are based on limit state design considering both the deformation of the structure which shall remain within appropriate limits and the resistance to rupture under expected loads. Moreover, timber beams should be sorted by lower limit in stiffness and strength. Unusual forms of construction like Notre-Dame are not covered and expert consideration is required.

2.3. Scientific knowledge on wood

Timber was studied as a structural material in civil engineering at the same time as other materials, from the beginning of 19th century and was an important structural material in the early ages of airplane manufacturing. In particular, military aeronautics research was very active in wood mechanics in Europe and the USA [10, 11, 12].

In the late 18th and early 19th the making of wood within the living tree was a controversy subject between botanists [13] until the discovery of cambium as a thin layer of stem cells producing both xylem and phloem [14]. At the same time technical progress in optical microscopy prove that wood is a cellular material similar to honeycomb with very small cell diameter (20 – 40 µm).

It was only during the 20th century and the invention of electronic microscopy that the fibre cell wall can be observed as a multi-layered fibre-composite at the nanometre level. X-ray diffraction made it possible to measure cellulose nano-fibre dimensions and orientation. In the second part of 20th century, chemical composition of wood as a mixture of bio-polymers with a whole cocktail of additives (small organic molecules) was elucidated with the help of mass spectroscopy and nuclear magnetic resonance spectroscopy. In the same period theoretical tools

in mechanical anisotropy which is typical of both honeycomb and fibre composites was developed [15] and applied to wood for airplane manufacturing [16].

3. “Squared timber” as a beam for building

Round-wood is a portion of trunk where connected branches are cut close to the trunk. It is approximately a long straight cylinder with some tiny curves from place to place. It was used directly as beam in many domestic building in the past. But round wood connexions are difficult to achieve [6] and squaring, i.e. cutting operation on the round wood in order to obtain plane parallel faces is a solution. We will use here the term “squared timber” for axe-hewn logs including the pith (bois de brin in French). This should be done with respect of Richards recommendations [17]: “Cutting wood consists of two distinct operations: cross severing the fibre and splitting the fibre parallel with its lamination” (Fig. 2). This technique ensures the perfect parallelism of wood grain direction with force direction at beam periphery, keeping the mechanical efficiency of the trunk: these squared timber beams have globally the same mechanical properties as than round-wood beams. But tiny local curves are still present, needing dunnage pieces for precise adjustments in framework building process.



*Fig. 2 Squaring an oak log by severing fibre and splitting (Photo Florian Carpentier)
Severing the fibre is done first every 50 cm by two axe cutting
Splitting a long 50 cm chips parallel to wood grain in then achieved*

3.1. Clear-wood and “squared timber” mechanical properties

A tree trunk is a beam subjected to high flexure forces under wind action. This beam is a succession of clear parts and connecting zones, with branch departures. In order to resist wind forces, connecting zones should be as resistant as clear parts. This is the result of tree growth by a kind of additive construction, optimizing fibres orientation in every part of the tree [18, 19]. The global mechanical properties of a sound trunk (without rot occurring sometimes within the trunk, often in connection zones with dead branches): flexure stiffness and strength, is

equivalent to clear wood parts properties [5]. Clear-wood specimens used in standards for measuring wood mechanical properties are issued from these trunk clear parts, keeping the parallel orientation of fibres in the rods [10].

Both for tree and for engineering purpose, minimizing weight for a given stiffness (elastic deformation under given forces) is important for bending beams [20]. This can be measured by the efficiency index $EI = MOE^{1/2}/D$ where MOE is the modulus of elasticity (MOE) in the beam direction and D the material density.

Two basic indicators control the elastic modulus (MOE) in the fibre direction for wood: its density (kg/m^3) signature of the honeycomb structure, and its specific modulus (SM) signature of the elastic behaviour of the cell wall. SM is the square value of sound speed in both cell wall and wood itself. It can be measured by acoustic methods [21]. The elastic modulus is the product of the two values D and SM: $MOE = D \cdot SM$. The efficiency index can be expressed through these two independent factors: $EI = \sqrt{SM/D}$.

Wood is a good material for music instrument partly because the speed of sound (4000 to 6000 m/s) is as high as for steel blade in a vibraphone. It is also the building material with the smallest density thus it is always efficient as bending beam. The best efficiency will be found for higher values of SM together with lower density, with is often the case for softwoods as spruce or fir.

Moreover, for a building material, stress at rupture in bending (MOR) and maximum strain (MS) before rupture are also important criteria. In structural mechanics, MOE is the key for calculation of local stresses and strains in the elastic domain, MOR or MS are “red” signals for overloading.

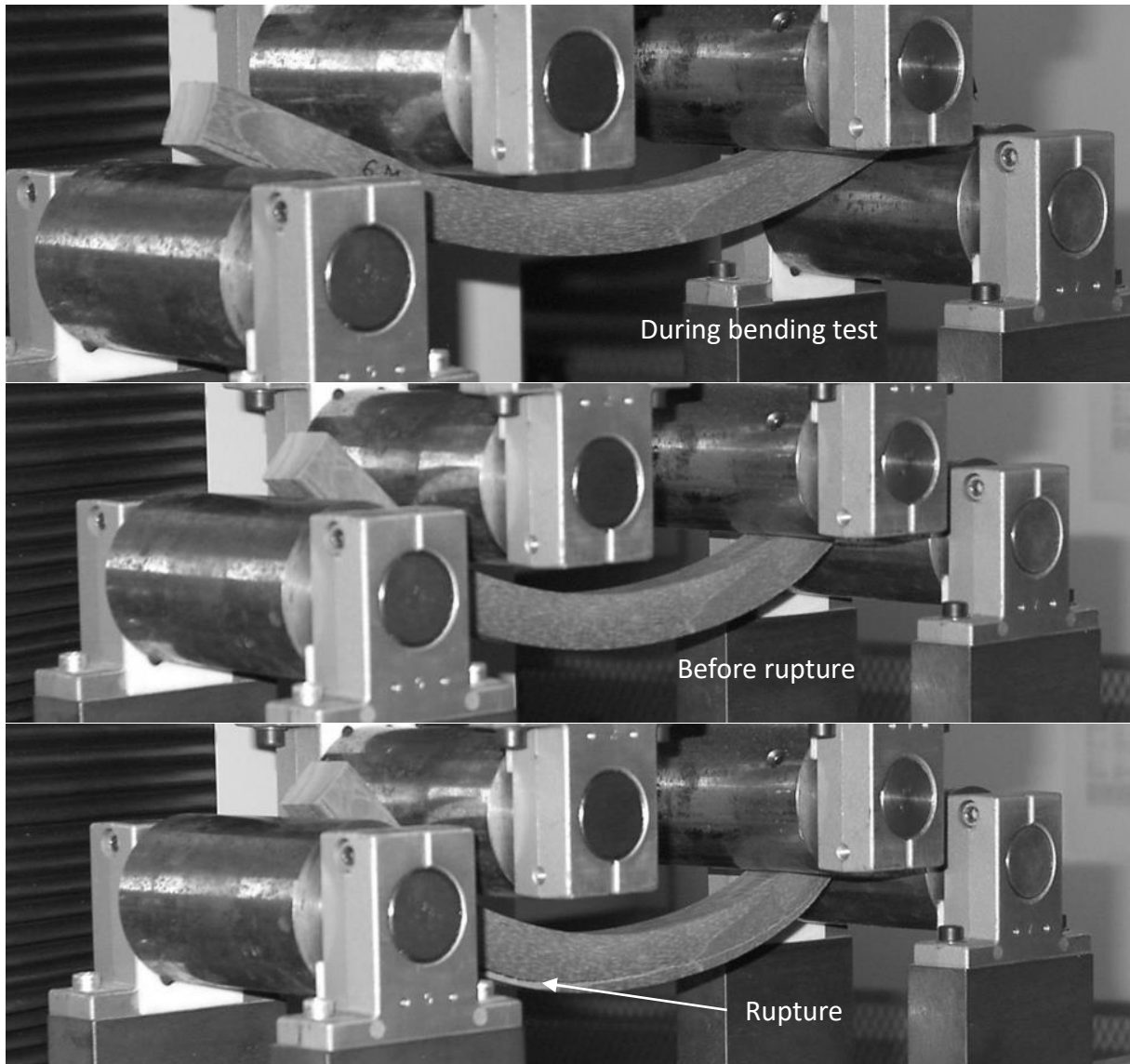


Fig. 3 Standard bending test for a clear wood rod (length 380 mm, section 20 mm x 20 mm)

The results on bending tests for clear-wood show that MS is high (Fig. 3). In a building, there are always maximum allowable beam deflexions for comfort reasons. The maximum deflection of a clear-wood beam as a trunk is very high (see deflexions of tall trees in strong winds) and not allowable in a building framework (or for a floor). Thus for round-wood beams, the use of MOE values is often sufficient in mechanical calculation in order to guarantee good building performance, provided that there are no big defects as internal rot zones within the trunk.

3.2.Eurocode 5 and timber mechanical properties

Due to its structure, wood is a highly anisotropic material [10, 12]: mechanical properties as stiffness (MOE) or strength (MOR) are ten times higher along the grain direction than along the transversal directions (Fig. 4). It should be noted that, apart from the first few degrees from grain direction (angle of fibre direction with beam direction), the mechanical properties drop off very quickly in the first 15 degrees.

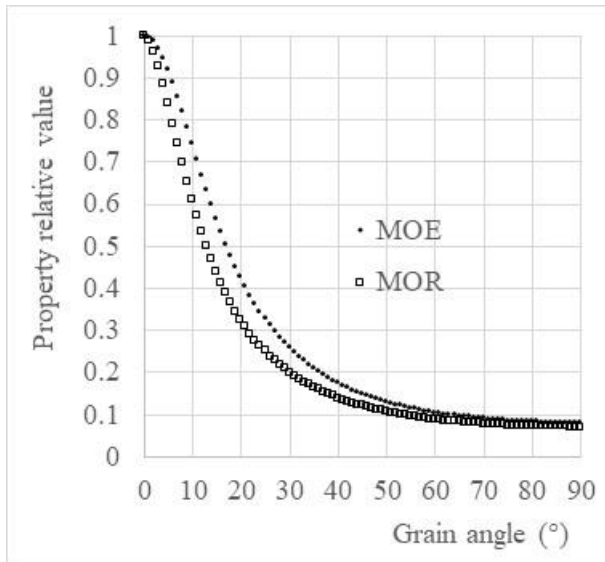


Fig. 4 Evolution of relative property with grain angle. Graph featuring Hankinson formula [10] 1: property for 0° grain angle, MOR: modulus of elasticity, MOR: bending strength

Eurocode 5 [9] is basically based on dry sawn timber. Sawing is the more common method of trunk deconstruction in order to produce straight beams. Unlike round-wood splitting, used to produce clear-wood boards for high value wooden products as dowel for barrels or sound-boards for musical instrument, basic sawing process cannot keep the integrity of branch connexions producing knots in the board and leads to local grain angle that can be rather high.

The dispersion of MOR values for sawn wood is very large and probability approaches are required by Eurocode 5. A very large quantity (1000) of representative sawn-boards from same species distributed on the whole supply zone are tested in bending until rupture and the MOR distribution is characterized by the 5th MOR percentile, which means that only 5% of the boards have a lower MOR. 5% is considered as an acceptable risk in building rules. Using the same probability approach for clear-wood and sawn-wood from the same trees shows that the 5th percentile can be nearly 3 times lower for sawn-wood (Table 2).

Table 2 Mechanical characteristics for mountain pine wood

Clear wood (183)	MOR (MPa)	MOE (GPa)
Mean	91.5	11.9
Percentile 5%	70.3	8.4
Percentile 95%	116.9	15.5
Boards (945)	MOR (MPa)	MOE (GPa)
Mean	48.0	9.1
Percentile 5%	24.4	6.1
Percentile 95%	73.8	12.5

Clear wood specimen and boards were sawn in the same trees
 In brackets: respectively, number of rod and of boards
 MOR: rupture resistance; MOE: modulus of elasticity

Both knots and local grain angle above 5° are mechanical defects for the beam and will lower

rigidity (MOE), resistance (MOR) and maximum strain (MS) at the same time. This is why the relationship between MOR and MOE for sawn-wood is strongly different from that for clear-wood coming from the same oak tree (Fig. 5).

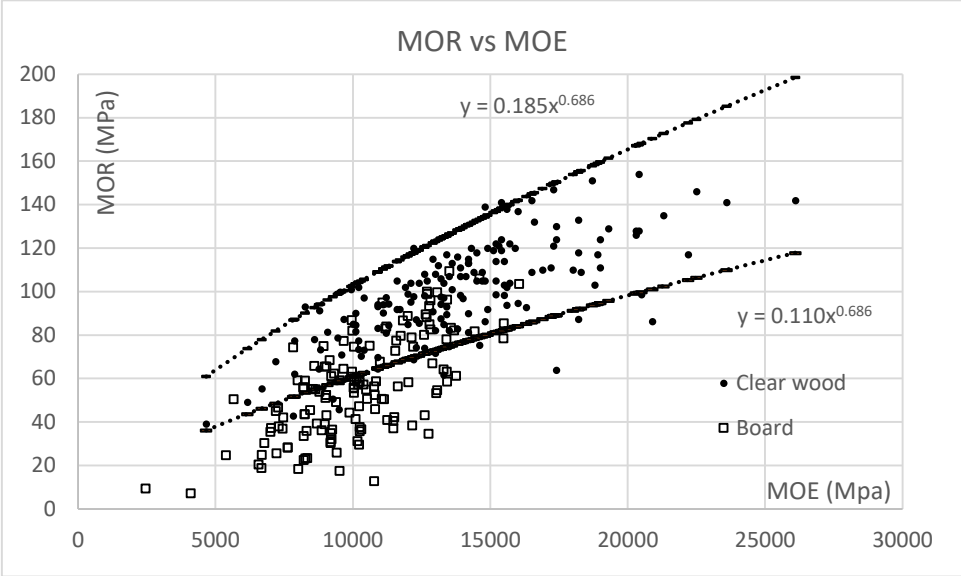


Fig. 5 Relationship between MOE and MOR for oak

*Results coming from Faydi PhD thesis [22]
 Clear wood: 139 rods coming from the 139 boards
 Regressions for clear wood: percentile 5% (lower curve); percentile 95% (higher curve)*

Eurocode 5 values for sawn-wood cannot be used for trunk timber [23]. Moreover, it seems unrealistic to test until bending rupture thousand trees of the same provenance. The relationship between MOE and MOR is similar (power law) for round wood (Fig. 6) and for clear wood (Fig. 5). Considering that clear wood and round wood properties, are the same, results on clear wood tests can be used to build the 5th lower percentile curve for MOR from known values of MOE, and this curve can be used to predict round wood MOR from its measured MOE.

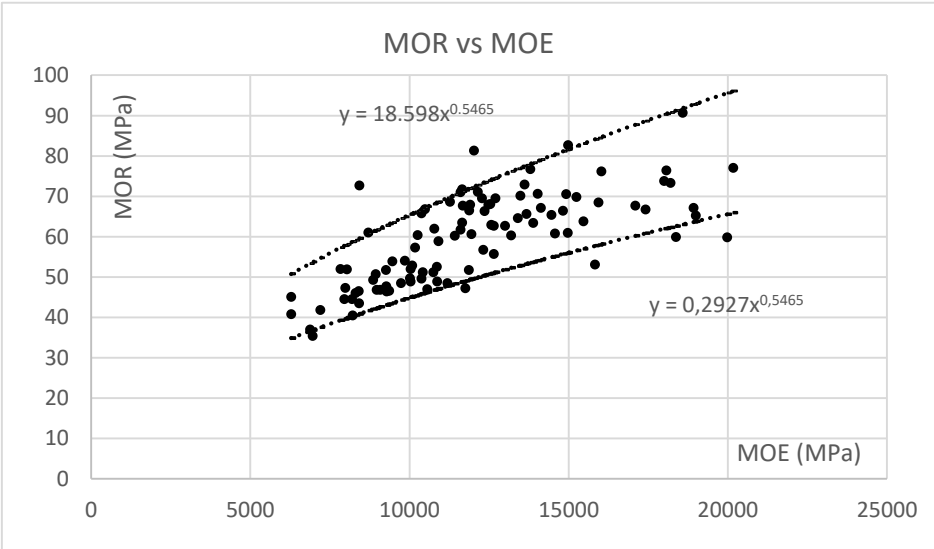


Fig. 6 Relationship between MOE and MOR for pine round wood

Results coming from Barnard PhD thesis [6] on 100 scots pine trees (poles)

Regressions for pine round wood: percentile 5% (lower curve); percentile 95% (higher curve)

A detailed 3D description of Middle ages framework before the fire is available for building information modelling (BIM) and simulation of the mechanical behaviour of the framework. A 3D description of each squared oak trunk together with values for their mean elastic modulus is enough to make the calculation and verify the maximum deflections or stresses in these beams.

An efficient procedure can be as follow: i) possible occurrence of big defects of the trunk is verified by man expertise or by X-ray tomography, ii) beam geometry is digitized by photogrammetry or Lidar, iii) mean modulus of elasticity for the beam is directly assessed by a bending test on the work site, iv) use a power law derived from clear wood tests for an estimation of a 5th percentile value of MOR . Each squared trunk beam gets an identifier (bar code or QR code) for all successive operations.

4. Oak timber choice

For today building, timber frame is often used but the rule is spruce dry sawn timber. Oak alone accounts for one fourth of the total standing tree volume in the French forest. Behind, fir and spruce account for 15%, pines for 13% and beech for 10%. Oak is abundant in nearly all French regions and was the natural frame material until the 18th century. Spruce and fir, abundant in the mountain regions, were used in these regions.

4.1.Mechanical properties

We have data on the mechanical properties for oak, spruce and fir species in the USA (Table 3). Spruce is a better choice for bending, when looking at the stiffness index, due both to a lower density and a higher specific modulus (Table 3). Oak have better transverse properties useful for good connexions, but this is not enough to explain permanent oak choice in French cathedrals.

Table 3 Mean mechanical properties for oak, spruce and fir.

Clear wood property (dry)	Oak	Spruce + Fir	Oak/Spruce+fir
Density (Kg/m ³)	670	380	1.76
MOR (MPa)	99.8	68.2	1.46
MOE (GPa)	12.0	10.4	1.16
MOR/MOE	8.31	6.58	1.26
Specific modulus (10 ⁶ m ² /s ²)	18.1	27.1	0.67
Efficiency index	5.2	8.5	0.61
Compressive strength parallel (MPa)	49.4	37.8	1.31
Comp. strength perpendicular (MPa)	8.1	3.3	2.42
Shear strength (MPa)	13.1	7.5	1.74
Transverse tensile strength (MPa)	5.6	2.1	2.62

Data are mean values for different species of oak and different species of spruce + fir in the US Forest [24]

4.2.Oak durability

The biggest difference between oak and spruce is the durability against insects and fungal attack. Oak wood is rich in additives of tannin family which can stop the insect risk and slow down the rotting process. Furthermore, if the timber is kept under shelter (roof) from the rain, it will be air dry and fungi can no longer be active in wood eating. Oak beams are everlasting under these conditions which is not so true for spruce and fir. As oak was very abundant at Cathedral periphery and Bishop want everlasting monuments, oak was a good choice.

We know today that rot resistance (measured by the mass loss during a standard test against fungi) of oak heartwood can be very different from tree to tree [25], from poorly durable (a minority of trees) to very durable (a majority of trees).

Table 4 Rot resistance of oak wood and ellagitannins content

Position	Nb spec.	ML	E. Tannin	Very durable	Poorly durable
Fourth quarter (close to the pith)	156	16%	69	44.2%	9.0%
Third quarter	139	13%	129	54.7%	4.3%
Second quarter	158	10%	220	65.8%	1.9%
First quarter (close to sapwood)	161	6%	414	84.5%	1.2%

Measures on 86 oak trees (160 years old at a mean) [25]

Nb spec.: number of oak specimen tested; ML: mass loss due to fungal attack

E. Tannin: indirect measure of ellagitannins content

Very durable: % of specimens in the highest class of natural durability in European standard

Poorly durable: % of specimens in the two (out of 5) lowest classes of natural durability

First to fourth quarter: 4 successive portions along a ray from sapwood limit to pith.

In the experiments, wood age varies from around 40 to around 140 years old from first to fourth quarter (Table 4). At the same time, ellagitannins content decreases strongly from high durability to poor durability. Durability decrease for the older wood rings, near the pith is due to chemical ageing of the tannins. Globally, young trees have a better mean resistance to rot risk. However, it can be useful to assess the rot resistance of the oak beams, knowing that a small percentage of trees have a low level of durability (and we do not have the empirical knowledge of Middle ages carpenters regarding the durability of oak provenance).

Today, wood oak is still widely used for wine or alcohol barrels. Tannin content is also important for barrel makers and they have developed a tool based on near infra-red spectroscopy (NIRS) in order to control their clear wood staves [26]. NIRS technique proves to be an efficient tool in order to get a good estimation of ellagitannins in oak wood, hence to grade oak timber for rot resistance.

4.3.Tree choice

In order to find 10 to 12 meters long beams, total height of the trees should be above 20 meters. For small diameter beams, the slenderness of the tree (total height divided by diameter at breast height) should be high (more than 70). This is not unusual (Table 1) but most of the oak trees have lower slenderness (below 50). Slender trees have higher values for sawn wood MOR and MOE (Fig. 7) and a lower taper which can be a reason for such choice by Middle ages carpenters.

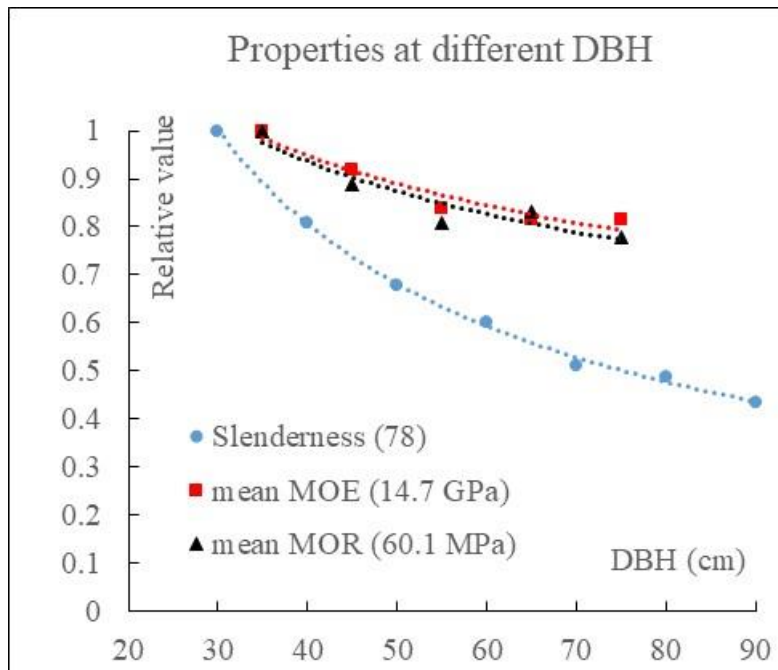


Fig. 7 Tree slenderness and timber properties for French oak sawn wood [27]

Values in the bracket are the maximum values (1 in relative value)

Relative value is the value divided by the maximum

Beams equivalent to Middle ages choice are the lowest diameter

DBH: diameter of the standing tree at breast height

5. Green round wood use

Using green wood is interesting for two main reasons: i) quick installation of beams after tree falling, ii) no energy input for wood drying.

5.1. Shrinkage of green round-wood

Green wood will dry during years following cathedral building, until moisture content equilibrium (ratio between mass of water and wood anhydrous mass) with the surrounding climate (standard dry wood has a moisture content around 12%). During drying there will be changes in timber dimension (shrinkage) with different values for each direction (Fig. 8). Tangential shrinkage is roughly twice the radial shrinkage while longitudinal shrinkage is generally considered as negligible compared to the shrinkage of the two other directions. Hence surface shrinkage is equal to volumetric shrinkage. The value for longitudinal shrinkage in long oak beams, around 15 mm from green to dry state should be taken into account as the thermal dilatations for steel or concrete beams.

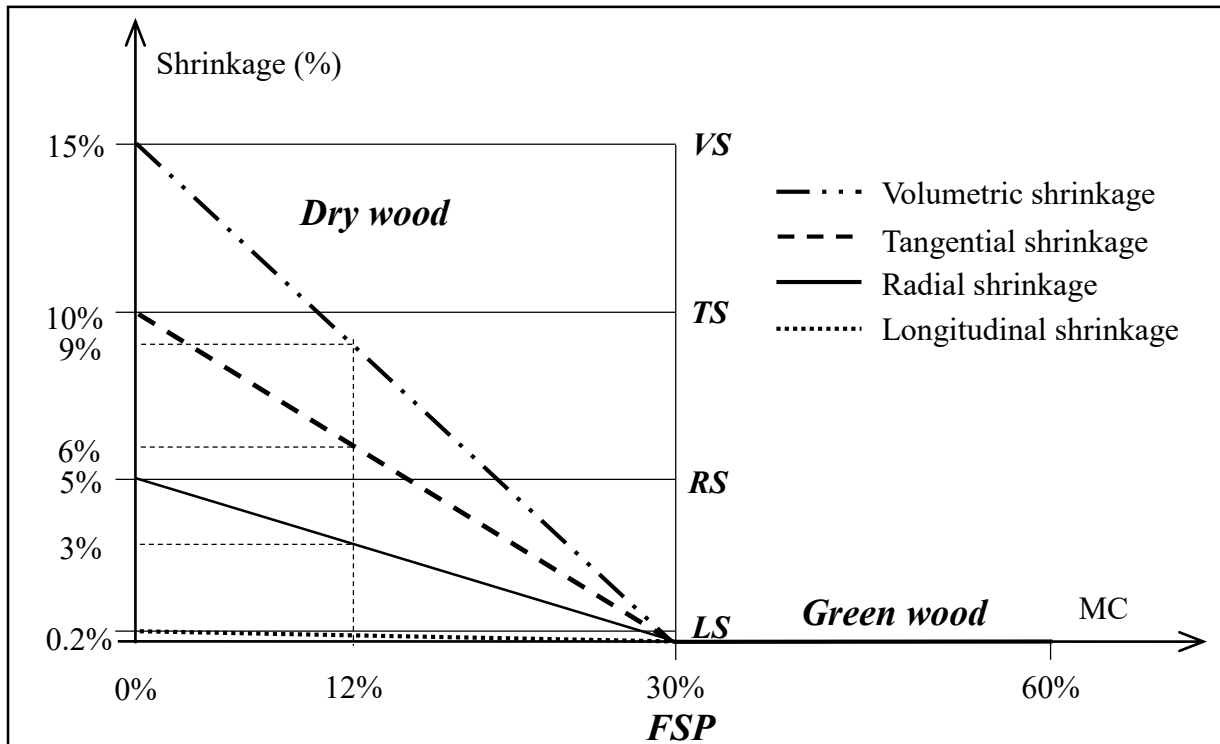
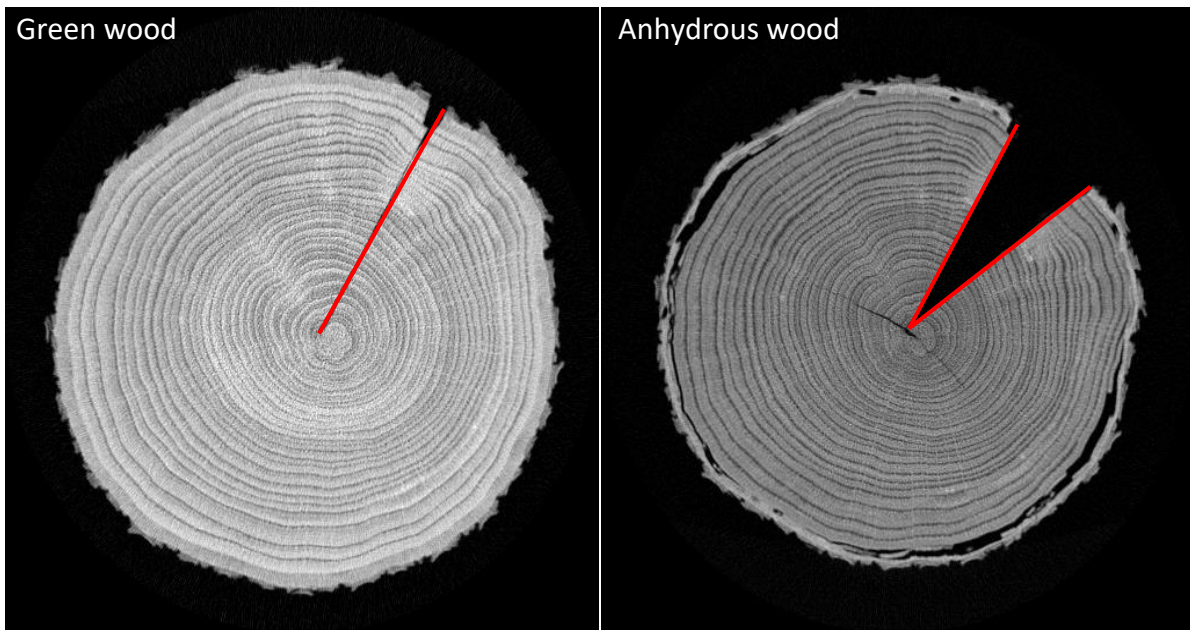


Fig. 8 Schematic diagram for oak shrinkage from green wood to anhydrous wood ($MC=0\%$) FSP: fibre saturation point; MC: wood moisture content (60% in the living tree at a mean for oak trees); VS: total volumetric shrinkage, TS: total tangential shrinkage, RS: total radial shrinkage; LS: total longitudinal shrinkage,

The great difference between radial and tangential shrinkage leads to a geometrical impossibility for round wood (Fig. 9). If a_t is the tangential shrinkage, a_r the radial shrinkage, R the log radius and C log perimeter at green state ($C = 2 \cdot \pi \cdot R$), after shrinkage, the new radius is $R_1 = R \cdot (1 - a_r)$ while the new perimeter is $C_1 = C \cdot (1 - a_t)$. But this perimeter is smaller than $C_2 = 2 \cdot \pi \cdot R_1$ and the perimeter length difference is $C_2 - C_1 = 2 \cdot \pi \cdot R \cdot (a_t - a_r)$. The relative (to initial perimeter) length difference is the value of the difference between tangential and radial shrinkage. In the case of oak (Fig. 8) drying from green state to 12% moisture content the values of shrinkage are 3% in radial direction, 6% in tangential direction and 9% in surface. The relative perimeter length difference will be 3% which is much higher than radial crushing strain. So, radial cracks from pith to periphery will occur during shrinkage from green to dry wood (Fig. 9).



*Fig. 9 Shrinkage of a log portion from green to anhydrous state (oak)
X-Ray transmission image (darker means lower density), Images from F. Mothe, INRAE Nancy)*

Fortunately, such longitudinal cracks do not influence the rigidity or the strength of the beam issued from straight grained trees [23, 28]. There is a 6% reduction of section area (surface shrinkage) meaning a 6% reduction in compression for a column. The second moment of inertia varies as the fourth power of the radius; this means a 12% reduction. Adding the void in the crack (3%), the total reduction in stiffness will be around 16% due to shrinkage until 12% moisture content. For the flexure strength the reduction will be a little lower (around 12%).

5.2. Change in mechanical properties between green and dry wood

There is always a very strong proportional relationship between green and air dry properties with coefficient of determination R^2 around 80% [29]. We can use data on the mechanical properties for oak species in the US oaks at green and dry state [24] in order to have a good estimate of the changes in mechanical properties from green to dry (12% moisture content) wood (Table 5).

Table 5 Changes in oak clear-wood mechanical properties from green to dry

Clear wood property (oak)	Green	Dry	D/G
Density (kg/m^3)	944	670	0.71
MOR (MPa)	59.6	99.8	1.67
MOE (GPa)	9.2	12.0	1.30
MOR/MOE	6.5	8.3	1.29
Specific modulus ($10^6 \text{ m}^2/\text{s}^2$)	15.6	18.1	1.16
Compressive strength parallel (MPa)	25.5	49.4	1.94
Comp. strength perpendicular (MPa)	5.1	8.1	1.58
Shear strength (MPa)	9.0	13.1	1.46
Transverse tensile strength (MPa)	5.1	5.6	1.08

Mean values for different American oaks.

Green moisture content is 60%, dry moisture content is 12%

D/G is the ratio between dry and wood state for each property

Except for transverse tensile strength (and of course density), all the mechanical properties are higher for dry wood, and for each case, the increase is greater than the reduction in geometry due to shrinkage: -16% for inertia compared to +30% in MOE; -6% for section area compared to + 94% in compressive strength; -12% in inertia contribution compared to + 67% in MOR. The reduction in density brings also a positive contribution by a decrease of the beam dead weight.

Globally the riskiest period is at the beginning of full loading for the green wood frame and high beam deflexion should be a rapid signal of misconception. This may explain how carpenter find a very good fitting of the frame without calculation.

5.3. Long term creep

Wood as a viscoelastic material will present a long term increasing of the initial elastic deformation called creep. The creep is known to be higher for green wood and even higher for a constant stress associated to moisture content changes. The coupling action between a permanent load and moisture content variation during the whole life of the frame (including initial drying), called mechanosorptive creep [18] should lead to a more important beam deflection. The subject is still a matter of active basic research and there are not yet results for oak beams. Information can be derived from the existing heritage for oak beams. Besides large variability in observed old beam deflections, they do not seem to be so large.

6. How new scientific knowledge may help for the restoration of Notre-Dame?

It seems quite clear that Middle ages carpenters had a keen knowledge of the timber they can harvest from well-known forests. They were probably aware of both mechanical, rot and insect resistance of the chosen timbers. We do not have this experience-based knowledge, but we have new scientific knowledge and modern tools available for sorting and grading.

We have, for Notre-Dame de Paris a full 3D description of the existing timber frame giving geometric parameters for sorting: length, diameter, slenderness, straightness. These parameters are registered in the national French forest inventory (<https://inventaire-forestier.ign.fr/>) helping the search for forest plots with the desired oak trees. Terrestrial or airborne LIDAR, if necessary can be used to help the final tree choice within the forest plot [30].

For the physical, mechanical and chemical pertinent parameters, the weight of wood (density), the sound of wood (specific modulus) and the taste of wood (ellagitannins content) are often use by artisans. We can use modern techniques as X-Ray tomography [31], vibration or ultrasound techniques [32, 33] and NIRS tools [26] so that we can have a good prediction of properties for modern computer aided building conception.

Moreover, rigidity and resistance of a wooden frame is also determined by connexions' resistance. As shown in [34] in 2014, some disorders have been observed in the frame of Notre-Dame with restorations probably undertaken during the Middle ages. The origin of these disorders are not well understood at the scale of the frame structure. It has been supposed that the local mechanical properties were weak, maybe due to high water content and fungi attack.

Innovations in pure wooden assembly were very active during cathedral building period [4, 35]. Mechanical behaviour of oak assembly during and after shrinkage is very poorly documented apart from the observations on cultural heritage [36]. Furthermore, many structural damages in wooden frame heritage come from connexions either due to high long-term moisture levels or to mechanical disorder [4] issuing sometime from shrinkage differences between wooden pieces (and possibly due to longitudinal shrinkage [36]). Anyway, the Middle ages best know-

how, documented by heritage, is well maintained by today carpenters keeping alive the Middle ages know-how as with the association *Carpenters without borders* [37] (Fig.10).

Studies combining experimental and numerical approaches are clearly needed in order to provide the basis for computer aided wood framing construction using green wood, in accordance with European standards and with the same efficiency as 800 years ago. This is part of the joint efforts piloted by CNRS task force in charge of coordinating the various research efforts and compiling the available data (<https://news.cnrs.fr/articles/notre-dame-research-steps-in>).

7. Conclusion

The choice of identical reconstruction of the timber frame of Notre-Dame de Paris, in accordance with Venice charter [38, 39], is relevant, considering the high level of description of the burned frame, the maintenance of Middle ages carpentry competence and the level of today scientific knowledge on timber properties.



Fig. 10 A copy of N° 7 frame, from Notre-Dame timber frame, built on site on the occasion of French cultural heritage day (September 2020) Photography: S. Caré

The frame reconstruction allows to conserve a witness of the architectural story (the cathedrals grow during de middle age). This worksite induced the conservation of trades and, it is also a way to re-discover “buried” human knowledge and nature building know-how. Wood and tree beams are common materials for building since the very beginning of humanity but the most recent scientific investigation attests their modernity as complex multi-scaled structural material highly competitive for light stiff structural members as in light airplane manufacturing [40].

Using tree-length oak material just squared at minimum and rapidly placed in the timber frame at green state does not only keep tree part performance. It is the highest possible environment-friendly choice: no pollution, very small energy use, full carbon storage as long or even longer, in the case of old cathedrals, as the forest carbon storage, easy low-cost recycling. It seems worth to re-start from Middle ages timber building knowledge in order to build innovations for better use of the huge availability and diversity and of oak trees for tomorrow material needs.

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