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ARGUMENTS FOR REUSING OLD OAK WOOD RECOVERED FROM DEMOLITION

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Abstract:

The main objective of this study was to find scientific arguments in favour of reusing recovered oak wood in order to reintegrate it in new types of structures. For this study six beams were selected, which had been recovered from a house built in 1831. Visual analysis revealed several defects and signs of degradation in the sapwood and inside the cracks. The recovered beams hadn't been treated with any toxic chemicals. Bending strength, modulus of elasticity and compression strength parallel to the grain were investigated and microscopy and FTIR-ATR spectroscopy were used to check the quality of the apparently sound beam areas also used for the determination of mechanical properties. Macroscopic and microscopic analysis may not reveal any incipient fungal attack but FTIR analysis was proven to be effective. The obtained results open a new perspective for the future use of recovered old oak wood, due to the adequate mechanical properties and to the assumed means of eliminating degraded areas.

Key words*: recovered wood; mechanical properties; decay; microscopy; FTIR analysis.*

INTRODUCTION

The construction and demolition (C&D) waste can be defined as waste material produced in the process of construction, renovation or demolition of structures (Statistics Canada 2000 in Yeheyis et al. 2012). The C&D is often a significant component, representing 20–30% and sometimes more than 50% of the total municipal solid waste. C&D waste is composed mainly of wood products (20-30%) asphalt, drywall, concrete and masonry (Yeheyis et al. 2012, Leopold et al. 2011). The main C&D waste management systems include waste avoidance and minimisation through recycling/reusing, waste to energy options (where possible) and safe disposal and discharge only as a last resort (Marchettini et al. 2007 in Yeheyis et al. 2012, Leopold et al. 2011).

The need to recycle aged wood has increased greatly over recent years. The cascade use of wood is one of the leading strategies in developed countries. One possible option is to use recovered wood as a source of energy. However, its application for furniture construction and interior design is preferable (Kránitz et al. 2010 in Thaler and Humar 2013). For these purposes, the relevant properties of aged wood must be known. Earlier studies of the mechanical properties of 200 years old English oak and Norway spruce from Poland and Switzerland showed that the modulus of elasticity of 200 years old wood and the freshly cut reference wood remained within the same range (Kránitz et al. 2010 in Thaler and Humar 2013). Thaler and Humar's findings clearly show that old wood is suitable for reuse and recycling if not damaged by fungi or insects. Their results confirmed that the strategy of the cascade use of wood is feasible and that wood can be used in more than one life cycle. Furthermore, old wood retains its natural properties so there is no need to replace old wooden constructions if the wood is sound and not attacked by fungi of insects (Thaler and Humar 2013).

At present, European oak (*Quercus robur* resp. *petraea*) is classified as 'durable' against fungal attack (durability class DC 2 for heartwood) according to EN 350-2 (1994). However, results from studies showed a variation in durability. Timber components might perform unexpectedly poor due to insufficient protection by misuse, design, low work execution level, or due to low resistance of the material in use (Brischke et al. 2012). Because bark consists of as much as 40% lignin, it is predisposed to decay by white-rot fungi (Vanea et al. 2006). The external surfaces of wooden elements are affected by rain and wind which bring small fragments of plant and animal origin, spores and microbial cells, as well as minerals and air pollutants. UV radiations are also an aggressive deterioration factor. The internal environment is usually more controlled than the outside, heating, air conditioning and humidifiers/dehumidifiers affecting factors that control microbial growth and survival. The nature of the coating also affects microbial development, some components being inhibitory and others stimulatory to growth. Materials such as cellulose derivatives can act as nutrients for fungal cells (Winters and Guidetti 1976, Allsopp et al. 2004a in Gaylarde et al. 2011), while organic solvents and heavy metals in pigments can adversely affect them (Gaylarde et al. 2011). Accordingly, wood undergoes complex biotic and non-biotic degradation and deterioration phenomena. Despite the fact that incipient decay may be difficult to detect visually with certainty, it can influence negatively some wood mechanical properties. Wilcox (Wilcox 1978) indicated that compression parallel to the grain and shear parallel to the grain can be reduced by approximately 20% before decay can be reliably identified as being present. Bending strength is more sensitive to incipient decay than compression or shear parallel to the grain (Carll and Highley 1999). Advanced decay has little effect on MoE (static bending), but modulus of rupture (MoR) is more likely to be reduced (Yang, Ilic and Wardlaw 2003). For many properties of aged wood no definite conclusions exist (Kranitz et al. 2014) and in order to elucidate more accurately the influence of the natural ageing on the relevant properties of wood further experiments have to be conducted on additional materials of different ages and to determine mechanical properties (Thaler and Humar 2013).

The main objective of this study was to investigate and determine the mechanical properties of recovered oak, *Quercus petrea (Matt.) Liebl.*, beams that had been in use for more than a century, in order to reintegrate them in new types of structures. Bending strength (MoR), modulus of elasticity (MoE) and compression parallel to grain ($\sigma_{C||}$) are the investigated mechanical properties. Visually examined, healthy beam areas were used for samples. FTIR spectroscopy (Faix et al. 1991, Pandey and Pittman 2003, Mohebby 2005, Neumann et al. 2007, Jelleab et al. 2012) combined with microscopy being reported to be useful to detect fungi in wood (Hoegger and Kües 2007), it was useful to check the quality of the apparently healthy beam areas also used for the determination of mechanical properties. The research carried out is part of larger investigation regarding the possibility of recycling recovered wood and wood-based materials later to be used in innovative panel structures for furniture.

Fig. 1.
House before demolition, 2000.

Fig. 2.
Beam with inscription: "Renovated in 1878".

Fig. 3.
Beams deposited in barn.

Fig. 4.
Cracks.

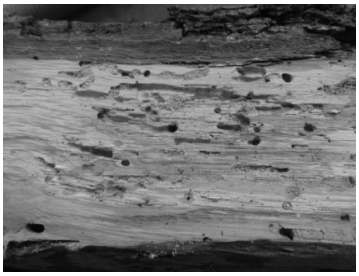


Fig. 5.
Insect attack and white rot.

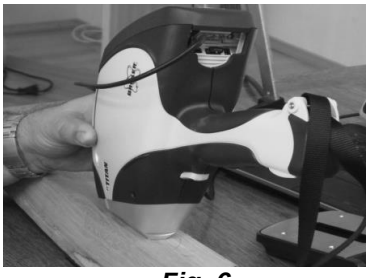


Fig. 6.
XRF Analysis with S1 TITAN Series Handheld XRF Analyzer

MATERIALS AND METHODS

For the study of the mechanical properties of old oak wood six beams were selected and investigated. The beams were recovered from a house (Fig. 1) in Crăciunel village, (Harghita County, Transylvania, Latitude: 46.183115°, Longitude: 25.429477°) built in 1831, renovated in 1878 (Fig. 2) and demolished in 2000. The structure of the demolished house consisted entirely of semi-carved round oak wood elements covered with plaster and lime. After demolition they were stored in a barn (Fig. 3) The beams chosen for testing were 4,323-5,420m long, contained bark tissue (less than 5%) as well as sapwood (less than 10%) and heartwood. Macroscopic investigations revealed several defects such as: traces of plaster and lime, dirty and aged surfaces, chisel marks, grooves and holes resulting from previous use of the beams, cracks along the grain and radial, both superficial and (10-90mm) deep, traces of inactive insect attacks, white and brown rot in the sapwood and along some of the cracks. Judging by the size, shape, colour and localisation of the insect galleries this attack had most likely been made by *Cerambycidae* insects. The recovered beams had not been treated with any toxic chemicals, such as CCA or lead based paint, as revealed by tests made with S1 TITAN Series Handheld XRF Analyzer showed (Fig. 5).

In order to identify variations of the mechanical properties along the beams, from each beam approximately 700mm long segments were cut, one from each end and one from the middle, resulting a total of 18 segments. Their deteriorated 100-300mm end parts were eliminated. Each segment was given a code containing the number of the beam from I to VI and the number of the segment: 1 for the thicker end, 2 for the middle part and 3 for the thinner end (Fig. 6). The beam segments had an irregular (between square and circular) cross section, with one or two carved sides and had variable dimensions between 243 x 202mm and 143 x 127mm.

Mechanical tests

From each segment samples were cut from the heartwood area for testing MoR, MoE and compression parallel to grain (Fig. 7, Table 1). The samples were cut avoiding all macroscopically visible defects and maintaining a radial orientation. The density was determined according to ISO 3131:1975.

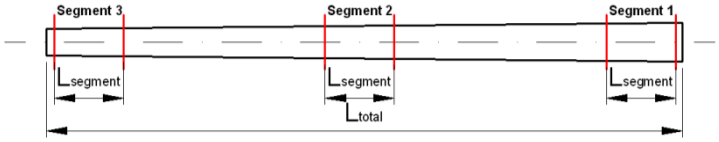


Fig. 7.
Segments. Position and length of the segments along the beam.

A Zwick/Roell Universal Test Machine was used. The maximum load was recorded with an accuracy of 1% of the measured value. The deflection in the middle of the test piece (below the loading head) was measured with an accuracy of 0,1mm and plot these values against the corresponding loads measured to an accuracy of 1% of the measured value. Data was registered with Text Expert II soft.

Table 1

Dimension and number of test pieces and mechanical testing methods

Test	Size of the test pieces, [mm]	Method	Formula		Number of test pieces
MoR	300±1 x 20±0,5 x 20±0,5	ISO 3133:1975	$MoR=3P_{max}l/(2bt^2)$	[N/mm^2]	67
MoE	300±1 x 20±0,5 x 20±0,5	ISO 3349:1975	$MoE=l^3(F_2-F_1)/[4bt^3(a_2-a_1)]$	[N/mm^2]	67
σ_{CII}	60±1 x 20±0,5 x 20±0,5	ISO 3387:1976	$\sigma_{CII}=P_{max}/(bh)$	[N/mm^2]	70

Where: *l* is the distance between the centres of the supports, in millimetres; *b* is the width of the test piece, in millimetres; *t* is the thickness of the test piece, in millimetres; *F*2 – *F*1 is the increment of load on the straight line portion of the load deflection curve, in N. *F*1 shall be approximately 10 % and *F*2 shall be approximately 40 % of the maximum load; *a*2 – *a*1 is the increment of deflection at the mid-length of the test piece (corresponding to *F*2 – *F*1), *P*max is the maximum load, in Newtons.

The experimental data was statistically processed according to ISO 2602–2:1981, by calculating the statistical mean $\bar{x}$, the standard deviation S and the lower limit of the confidence interval $L^q_{5\%}$, which eliminates eventual errors.

Microscopic investigation

Following the macroscopic investigation, small samples of approximately 8x8x30mm were extracted from beam II segment 1 from three anatomically significant areas: sapwood with discoloration (sample code: z33a), heartwood with discoloration (sample code: z15d), apparently healthy heartwood (sample code: z15b), and a middle area between sapwood and heartwood (sample code: z21m) (Table 2). The samples were plasticised by boiling in distilled water after which they were transferred into a solution of ethyl alcohol and glycerol (1/1). Afterwards they were sliced into 60µm thick micro-sections with a sliding microtome, 4 slices for each sample. solutions of 1% concentration of Safranin and Astra Blue were used in successive steps to color samples, colouring time being 2 min for each, in order to improve contrast and better visualize or differentiate healthy and decayed areas. Safranin stains in red lignin regardless whether cellulose is present or not and Astra-blue shows affinity for cellulose and is incorporated into cellulose fibers only in the absence of lignin (Schwarze 2007, Srebotnik and Messner 1994). Following this procedure, de-lignified areas should be highlighted as blue areas on a red background. The stained and washed micro-sections were temporarily mounted in water and glycerol and investigated under an optical microscope Biostar Optech B5 fitted with a camera for image capture. The samples were observed in transmitted light at varoius magnifications.

FTIR analysis

The previously cut, uncoloured micro-sections from beam II segment 1 were used for analysis by FTIR (Fourier Transform Infra Red Spectrometry). Other three samples were taken from the same beam segment from sapwood areas affected by white and brown rot and from the healthy heartwood (Table 2). The affected wood was very soft and fragile so the samples were extracted by cutting with a sharp blade and were afterwards crushed mechanically to form a powder.

An Alpha Bruker FTIR spectrometer with ATR (Attenuation Total Reflection) device, connected to a PC was employed for recording the spectra, which were further processed with the Opus 90 special software. The scanning range was 4000 – 400cm^{-1} with a resolution of 4cm^{-1} in reflectance mode, each spectrum being the average of 24 successive recordings. For each sample three spectra were recorded, baseline corrected, smoothened and further an average spectra was calculated. For comparison the average spectra were normalized. The average, normalised spectra of the experimental samples were compared with a reference spectrum of new healthy oak wood, considered as control. Assignment of the main absorption bands in the FTIR spectra, reflecting the extremely complex multi-polymeric structure of wood, was based on literature (Neumann et al. 2007).

Table 2

Sample codes and description for microscopy and FTIR

Test	Sample code	Description	Sample type
Microscopy and FTIR	z15b	Healthy heartwood, no discoloration, hard	micro-section, 60µm thick
Microscopy and FTIR	z15d	Heartwood with slightly white discoloration, hard	micro-section, 60µm thick
Microscopy and FTIR	z21m	Middle area between sapwood and heartwood, hard	micro-section, 60µm thick
Microscopy and FTIR	z33a	Sapwood with white discoloration, hard	micro-section, 60µm thick
FTIR	PA	Sapwood with visible advanced white rot, soft and fragile	powder
FTIR	PB	Sapwood with visible advanced brown rot, soft and fragile	powder
FTIR	LS	Healthy heartwood, no discoloration, hard	powder

RESULTS AND DISCUSSIONS

Mechanical tests

Density values for MoR, MoE and compression parallel to grain for recovered oak are shown in Table 3. MoR for recovered oak tended to be less, by 11.5% and 27%, than values obtained by Thaler and Humar 2013 and Fojutowski et al. 2014 (Table 4). MoE for recovered oak showed higher values by 17%, 32% than values reported by literature (Thaler and Humar 2013) and 4.5% lower than values reported by Fojutowski et al. 2014, and Wagenfür 2007.

Table 3

Density, MoR, MoE and σ_{CII} for recovered oak

	Density [Kg/m^3]	MoR [N/mm^2]	MoE [N/mm^2]	σ_{CII} [N/mm^2]
X_{mean}	686.619	85.715	9210.833	51.96
X_s	52.984	12.482	1401.843	6.583084
$L^q_{5\%}$	675.174	83.019	8908.035	50.536

The values of compression parallel to grain showed only minor differences for recovered oak wood compared to results reported in literature for recovered and control oak wood (Table 4) excepting Fojutowski et al. 2014. Values for recovered oak were 18.5% lower than values obtained by Fojutowski et al. 2014.

Table 4

Comparison of density, MoR, MoE and σ_{CII} between results for recovered oak and values in literature

Test	Recovered oak (*Q. petraea.)*	Recovered oak *(Q. sp.)* (Thaler and Humar, 2013)	Control wood *(Q. sp.)* (Thaler and Humar, 2013)	Control wood *(Q. robur L.)* (Fojutowski et al., 2014)	Oak wood *(Q. robur L.)* (Wagenfür, 2007)
Density [Kg/m^3]	675.174	820	611	668	430 ... 690 ... 960
MoR. [N/mm^2]	83.019	93.8	94.5	114	78 ... 110 ... 117
MoE. [N/mm^2]	8908.035	7573	6709	9325	9200 ... 13000...13500
σ_{CII} [N/mm^2]	50.536	47.0	46.9	62	48 ... 65 ... 70

Comparing the values between the three segments (Figs. 8-10) show a similar pattern in case of MoR, MoE and compression parallel to grain: segment 1 has values higher by c. 10% than segment 2 and 3 in case of MoR and compression parallel to grain, and 17% higher than segment 2 in case of MoE. Results of MoE for segment 1 are 5.5% higher than for segment 3. The values for segment 2 are less than 0.16% than values for segment 3 in case of MoR, for MoE are less than c. 13% and are less than 2% for compression parallel to grain. These results are similar to reported findings (Olărescu et al. 2013) acording to which all of the three mechanical properties have the highest values in the first third of the bole.

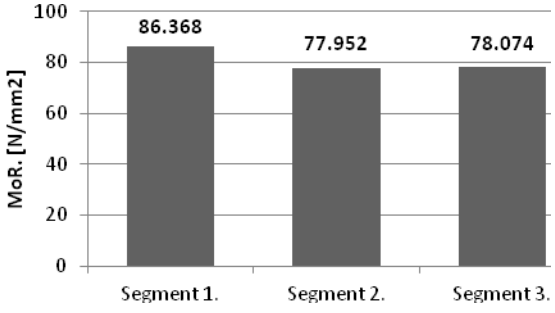


Fig. 8.
Comparison of MoR for the three segments.

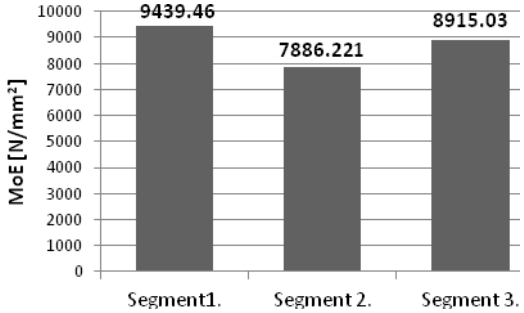


Fig. 9.
Comparison of MoE for the three segments.

Detailed comparison made between the MoR, MoE and σ_{CII} of segments 1, 2, and 3 of beams I-VI show with few exceptions a relatively uniform distribution of values (Figs. 8-10). In case of future confirmation of such distributions it is possible to foresee that the sound parts of recovered oak beams may be seen as a reliable source of material, to be used in new structures.

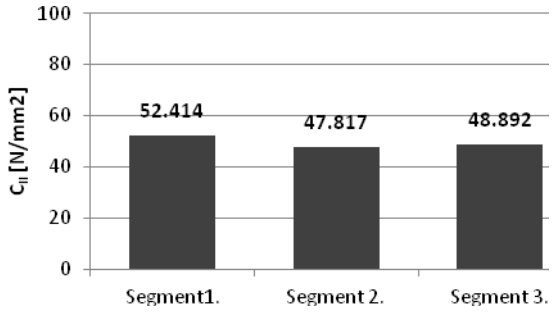


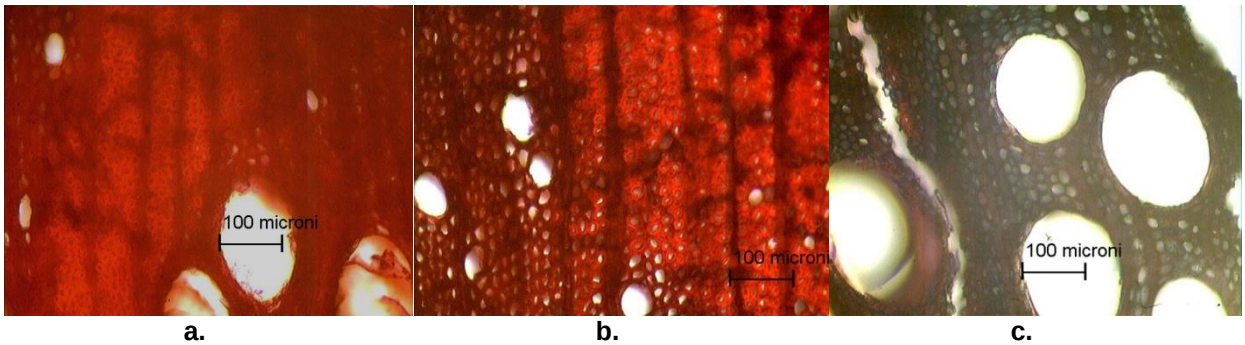
Fig. 10.
Comparison of C_{II} for the three segments.

Microscopic investigation

The presence of hyphae was not visible which indicates which most likely indcates that there is no active fungal attack, but does not exclude the presence of fungi in the past. Wood-inhabiting fungi are capable of becoming dormant if moisture conditions fall much below the range of fiber saturation, surviving in a dormant vegetative state, and reviving once moisture conditions again reach levels around fiber saturation. Common decayers of exterior woodwork have demonstrated an ability to survive periods of desiccation as long as a decade (Carll and Highley 1999).

Samples taken from heartwood and the middle area between sapwood and heartwood observed by microscope were red coloured and the structure of cells seem not to be affected (Fig. 11b). In the sapwood area (Fig. 11c) partially de-lignified bluish areas appear in the parenchyma cells which have been regarded as strongly susceptible to decay (Schwarze 2007). The partially de-lignified areas may suggest a previous attack of white rot fungi (Blanchette 2000). The reddish colour of the fibres areas could indicate a relatively healthy wood (Beldean and Timar 2013).

However the absence of any change in wood structure does not negate the possibility of decay because it may not occur in the small samples of wood chosen for study. The degree of decay can vary considerably over short distances and microscopic diagnosis of no presence of decay may be unreliable (Carll and Highley 1999). The microscopic investigation should be correlated with other types of investigations such as FTIR and mechanical testing (Beldean and Timar 2013).



a. **b.** **c.**

Fig. 11.
Microscopic aspects of the cross section of different samples (original magnification 200x): a. sound wood (control wood); b. sample Z21m indicating sound wood; c. sample Z33a revealing delignigied areas coloured in blue.

FTIR analysis

The healthy heartwood (Figs. 13, 15 and 17) spectrum presents some minor differences compared to control wood. The bands at 1594 and 1323cm^{-1} are more accentuated in relation to the neighbouring peaks in healthy recovered wood (LS, Z21m and Z15b). Bands between 1594-1599cm^{-1} are associated with C=C stretching vibrations of aromatic ring in lignin and bands between 1320-

1330cm^{-1} are characteristic to C–H vibrations in cellulose and a C–O vibration in syringyl derivatives, a main component of lignin (Faix 1991, Pandley and Pitman 2003).

In samples affected by white rot (PA, Fig. 12) results revealed increased intensity at 1635.99cm^{-1} band attributed to conjugated carbonyl groups originating from lignin and absorbed O-H, while the aromatic skeletal vibration band at 1596cm^{-1} decreased in intensity (Mohebby 2005). The white rot fungi decreased the band at 1155.4cm^{-1} C–O–C antysimmetric bridge stretching vibration in cellulose and hemicellulose (Faix 1991, Pandey and Pitman 2003) which suggests breaking of cellulose chains and shows signs of depolymerization. The decrease in intensity of 1117cm-^{1} band present in the results, characteristic to aromatic ring stretching, is attributed to structural degradation of lignin (Darwish, El Hadidi and Mansour 2013).

On the spectrum of wood decayed by brown rot (PB, Fig. 12) the increased intensity of aromatic skeletal vibration in lignin at 1594.64cm^{-1}, 1503cm^{-1} and of C-H deformation in lignin at 1455cm^{-1} may suggest that as decay progresses, extensive carbohydrate loss occurs and lignin concentrations increase in the residual wood (Faix 1991, Pandey and Pitman 2003, Darwish, El Hadidi and Mansour 2013). The decrease in intensity of the 1368,89 band of C-H deformation in carbohydrates like cellulose and hemicelluloses is attributed to wood degradation. Infection by fungi caused a sharp decrease in the intensities of the C-O stretch in cellulose and hemicellulose band at 1027.63cm^{-1} and the disappearance of the band at 1155.4cm^{-1} characteristic to C–O–C antysimmetric bridge stretching vibration in cellulose and hemicellulose. The decreased intensity of 1155.4cm^{-1} indicates advanced breaking of cellulose chains and shows that depolymerization may have occurred (Faix 1991, Pandey and Pitman 2003, Darwish, El Hadidi and Mansour 2013). The band at 899.61cm^{-1} also decreased in intensity which is associated to C–H deformation in cellulose. New bands appeared in the region between 1323-1232cm-^{1} and at 831cm^{-1} due to breakdown of chemical compounds in wood caused by fungi (Mohebby 2005).

Although the microscopic analysis didn't reveal traces of fungal attack on the heartwood samples z15d FTIR tests show the decrease of band at 1564.54cm^{-1} (Fig. 16). This change can also be observed (Fig. 14) in the sapwood with discoloration Z33a. The absence or decrease of these bands is characteristics of lignin and indicates decomposition of the aromatic skeleton of lignin (Darwish, El Hadidi and Mansour 2013). This may indicate an incipient stage of white rot fungal attack.

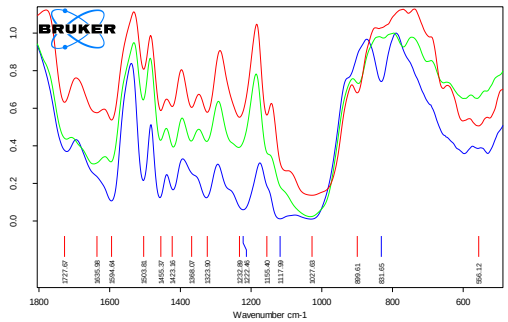


Fig. 12.
Sample PA (green) and PB (blue). Fingerprint spectrum of sapwood with white rot, brown rot and control wood (red).

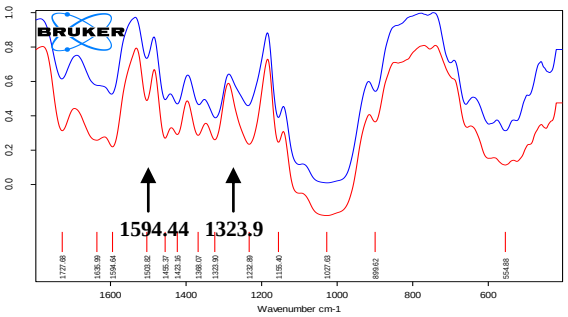


Fig. 13.
Sample LS (blue). Fingerprint spectrum of healthy heartwood and control wood (red).

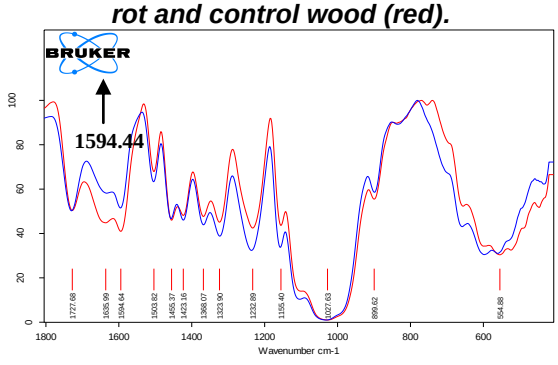


Fig. 14.
Sample Z33a (blue). Fingerprint spectrum of sapwood with discoloration and control wood (red).

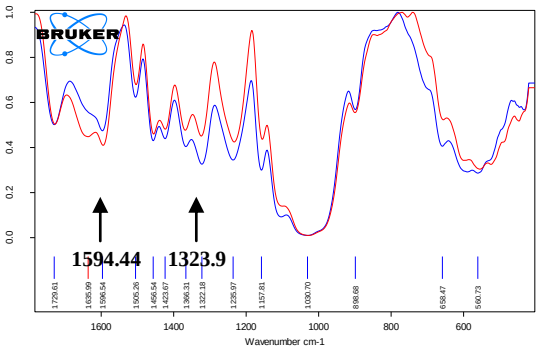


Fig. 15.
Sample Z21m (blue). Fingerprint spectrum of middle area between sapwood and heartwood and control wood (red).

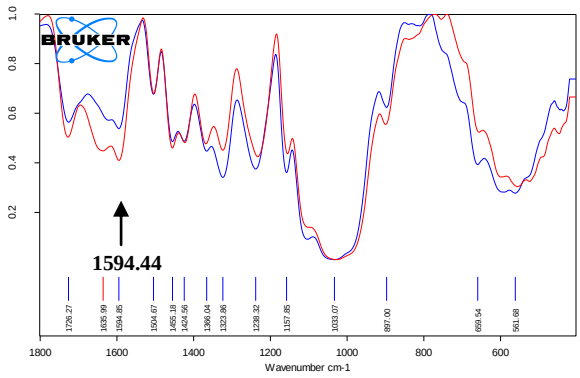


Fig. 16.
Sample z15d (blue) Fingerprint spectrum of heartwood with discoloration and control wood (red).

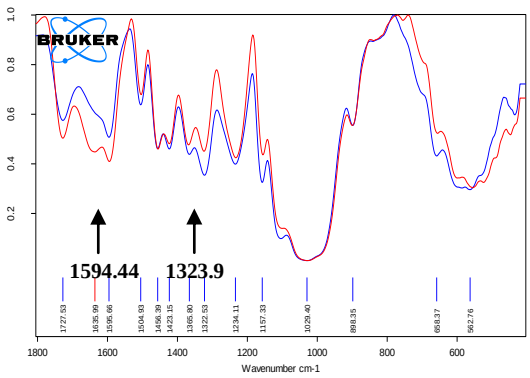


Fig. 17.
Sample z15b (blue). Fingerprint spectrum of healthy heartwood with no discoloration and control wood (red).

CONCLUSIONS

The results of the investigation, made upon more than 150 years old oak beams of certified origin are able to highlight future use of recovered oak wood. This study shows that the mechanical properties of old compared to new oak wood are significantly encouraging. Density, MoR, MoE and σ_{CII} for recovered oak were compared with results indicated by literature for new oak wood**.** The values of recovered oak density (675.174kg/m^3), MoR (3.019N/mm^2) and σ_{CII} (50.356N/mm^2) are within the indicated value limits for oak wood. The module of elasticity (8908.035N/mm^2) is slightly lower than the inferior value limit (9200N/mm^2) of new oak. There also are differences between the measured density, MoR, MoE and σ_{CII} and the respective values indicated by Thaler and Humar.

Microscopic diagnosis of no presence of decay may be unreliable as was observed in case of heartwood samples with visible discoloration (Z15d) which turned out to show signs of delignification in the FTIR analysis. This unreliability originates from the fact that the degree of decay can vary considerably over short distances. These results are consistent to reported findings of Blanchette according to which white-rot fungi have the capability to degrade lignin as well as other wood cell-wall components such as hemicelluloses and cellulose, causing a loss in strength gradually, until the wood becomes spongy to the touch. The wood infested with brown rot, which attacks primarily cell wall carbohydrates, can be greatly weakened even before decay is visible. The decaying effect of the fungi can be recorded in the FTIR analysis.

As macroscopic and microscopic analysis may not reveal any incipient fungal attack an antifungal treatment is advised before reuse. Due to the fact that accessibility to microscopy and FTIR may be restricted in a real life scenario of applying reuse and recycling to an industrial and semi industrial scale, macroscopic investigations remain a very important and useful method of selecting sound wood with the required mechanical properties.

The study encourages the future use of old oak wood recovered from C&D due to its reasonable mechanical properties and to the assumed ways of identifying and eliminating areas of degradation or by antifungal treating. A good perspective is now opened for its future use in association with recycled wood-based materials like blockboard and particleboard.

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