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Assessment of Condition of Wooden Mill in Kovačevići Area in Bosnia and Herzegovina

Procjena stanja drvenog mlina na području Kovačevića u Bosni i Hercegovini

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ABSTRACT • *Wood is one of the most important materials that has been used for several millennia. It is therefore not surprising that wood plays an important role in the cultural and technical heritage of several European countries and beyond. An excellent example of cultural and technical heritage is a wooden mill, almost 100-year-old, near Cazin in Bosnia and Herzegovina. These mills played an important role, especially in times of Bosnian war (1992-95), when this region was cut off from electricity. The microscopic analysis of the wood materials used in the mills revealed that the mills were made of chestnut (Castanea sativa) and oak (Quercus sp.) wood. Sufficient durability of these wood species resulted in good structural integrity of the mills. The surface of the wood materials in the mills showed partial degradation patterns caused by weathering over the years. However, the interior parts of the wood materials were intact probably due to smoke deposits from the open fireplace. It is suggested that the roofing in the mills should be maintained regularly to prevent possible leaks to protect this heritage for future generations.*

KEYWORDS: *cultural heritage; technical heritage; wood; non-destructive assessment; decay*

SAŽETAK • *Drvo je jedan od najvažnijih materijala koji se u industriji i graditeljstvu upotrebljava već nekoliko tisućljeća. Stoga ne čudi da drvo ima važnu ulogu u kulturnoj i tehničkoj baštini više europskih zemalja. Izvrstan primjer kulturnoga i tehničkog nasljeđa drveni je mlin u blizini Cazina, u Bosni i Hercegovini. Takvi su drveni mlinovi imali izrazito važnu ulogu u ratnim vremenima, kada je na ovom području bila prekinuta opskrba električnom energijom. Mikroskopskom analizom utvrđeno je da su mlinovi najčešće izgrađeni od drva pitomog kestena (Castanea sativa) i drva hrasta (Quercus sp.). Dobra trajnost pojedinih vrsta drva od kojih su mlinovi izgrađeni rezultirala je njihovom dobrom strukturnom cjelovitošću. Površina drva promatranog mlina djelomično je oštećena vremenskim utjecajima. Interijer je zaštićen od biološke razgradnje zbog naslaga dima koji je dolazio s otvorenog kamina. Važno je naglasiti da krovište drvenih mlinova treba redovito održavati kako bi se spriječilo potencijalno prokišnjavanje te baština zaštitila za buduće generacije.*

KLJUČNE RIJEČI: *kulturna baština; tehnička baština; drvo; nerazorna procjena; propadanje*

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1 INTRODUCTION
1. UVOD

Wood is subjected to biotic and abiotic degradation processes when used in outdoor applications (Eaton and Hale, 1993; Hasan *et al.*, 2008). In nature, these processes are desirable and necessary as they contribute to the carbon cycle and soil formation. However, when wood is used for technical purposes (constructions, bridges, buildings), the degradation processes should be slowed down as much as possible. Under favourable conditions, wood can become a nutrient for a variety of organisms that degrade one or more components of the wood to the point where they can metabolise them. Among biotic decomposers, fungi cause the most damage, while insects cause somewhat less damage in temperate climates (Schmidt, 2006; Humar *et al.*, 2020).

The intensity of decomposition of wood has increased in the last decade due to climate change. Wood, in similar applications, is decaying faster today than it did decades ago. This difference is most pronounced in Alpine valleys (Humar *et al.*, 2021; Van Niekerk *et al.*, 2022). The main reasons for the increased fungal decay intensity are higher temperatures, milder winters and more precipitation in the winter months (Humar *et al.*, 2021).

Wood has been one of the most widely used materials by mankind in the course of its long evolutionary history. Wood has been used for structural applications and for decorative, ritual and religious purposes. People's close association with wood over thousands of years has been embedded in the cultural heritage made of wood and represents people's lives and values (Kim and Singh, 2016). Many of the historic objects made of wood reflect the availability of wood and the processing tradition as well as its natural origin and beauty (Lo Monaco *et al.*, 2018).

The water mills in the Kovačevići and Cazin area are a testimony to the ingenuity and resourcefulness of the local people in using the natural resources at their disposal. These mills were used to grind wheat and maize and provided the local population with flour and other essentials. All the mills had been built by the local communities of Ćoralići and Liskovac. The importance of these water mills cannot be overestimated, as they had played a crucial role in the survival of local communities, especially in times of war during WWII and the Bosnian war (1992-95). However, the need for water mills declined over time, and many were abandoned (Čekić, 2021). In Kovačevići, there are five wooden mills, while in the Cazin area, there are approximately 50 such water mills.

They remain important for the cultural and technical heritage of Bosnia and Herzegovina. Each of these mills had its own name, reflecting local traditions and culture. For example, "Vilenica", one of the older water mills in the area, was built by the local Kovačević family. Other mills were named after their location or owners, such as Novak, Čardak, Mali mlin and Mlin Slap. The construction of the water mills was crucial for their functioning, as the water flow had to be regulated to ensure enough energy to drive the millstones. Most of the mills were built from local, durable wood species such as sweet chestnut (*Castanea sativa* Mill) and oak (*Quercus sp.*) (Čekić, 2021).

The chestnut and oak forests in Bosnian Krajina are well known. They are widespread in the wider surroundings of Cazin, Velika Kladuša, Bužim and part of Bosanska Krupa. According to the forest inventory in Bosnia, oak grows on more than 8000 ha and sweet chestnut on 6000 ha of the forests in Una-Sana Canton, providing natural material for a wide range of uses (Federalna uprava za šumarstvo, 2012). Oak and sweet chestnut are ring-porous species with coloured heartwood. The sapwood is usually narrow. Large vessels in the early wood are typical for oak (diameter over 200 µm) and somewhat smaller for the sweet chestnut, and radially oriented groups of small vessels in latewood. In addition, rays are clearly visible in oak species, while in sweet chestnut wood rays are visible only under magnification (Wagenführ, 2014). Oak wood is traditionally used for the production of wooden structures, bridges, railway slippers, barrels and furniture (Dogu *et al.*, 2017). Oak wood is characterised by high variability in durability and is therefore classified in durability classes from DC 2 (durable) to DC 4 (less durable) according to EN 350 (Brischke *et al.*, 2013; Meyer *et al.*, 2014). The reason for the classification of oak wood in low durability classes is related to the high variability of the chemical and anatomical structure of wood (Meyer *et al.*, 2014). Part of the variability can be related to the ring width. It is reported that the durability of oak with a ring width of less than 1 mm is comparable to that of beech. The vessels dominate the narrower sapwood with large lumens, which reduces the effectiveness of water exclusion and durability (Humar *et al.*, 2008). On the other hand, sweet chestnut is the most durable wood species in Europe, along with black locust (*Robinia pseudoacacia* L.), with much less variation in durability (Diamandis, 2010; Eichhorn *et al.*, 2017).

Oak and sweet chestnut wood is decomposed by both white rot fungi (e.g. *Donkioporia expansa* (Desm.) Kotlába & Pouzar, *Laetiporus sulphureus* (Bull.) Murrill, *Trametes versicolor* (L.) Lloyd, *Stereum hirsutum* (Willd.) Pers) and brown rot fungi (*Daedalea quercina* (L.) Pers., *Antrodia sp.*) (Schmidt 2006). Insects that attack older oak wood include *Bostrychus capucinus* L. and *Anobium punctatum* De Geer. Ants (*Formica sp.*)

have recently become more common on wood including oak wood (Unger *et al*., 2001; Humar *et al*., 2022).

After the end of the Bosnian war (1992-1995), the need for water mills was no longer present and they were abandoned. However, these mills have recently become a symbol of Gračanica and the local communities. As they were not properly maintained after the war, they started to deteriorate. Therefore, efforts have been made to preserve and restore them for future generations. Thus, it is necessary to determine their condition in order to prepare recommendations for conservation and protection for future generations. Moreover, the mills are an excellent example to study the performance of wood in harsh environments.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

The analysis was carried out at one single mill (Figure 1) founded at the entrance to the gorge of the Gračarica River near the village of Kovačevići (GPS coordinates: 45.020898, 15.871152), whilst there are several other mills at this location. The investigated mill is a representative example of traditional architecture and construction. It was powered by water as the region was cut off from the leading electricity grid during the war in the 1990s. The wooden mill in question was built in the early 1930s and rebuilt after the floods of 1962. The majority of the construction is almost 100 y old. In the 60s the roofing, water wheel and water channels were rebuilt. The analysis of the mill described in this paper was carried out on November 16, 2022.

Fungal spore concentrations found in the air were determined at four sites: two indoors and two outdoors. The control was outdoor air. PDA (Potato Dextrose Agar) medium (Difco) was used as the medium. Namely, 100 L air samples were taken. MAS-100 VF sampler from Merck was used. After sampling, the media plates were sealed with parafilm and incubated at 25 °C

Figure 1 Water mill in the area of Kovačevići
Slika 1. Vodeni mlin u naselju Kovačevići

in a dark climate chamber. The plates were inspected daily and after 72 hours the colonies grown were identified and the number of colony forming units (CFU) per m^3 (CFU/m^3) was calculated. The presence of spores was determined, and only the crucial individual species were identified.

The moisture content of the wood in the watermill was determined using an electrical resistance metre from GANN (Gann GmbH, Gerlingen, Germany), which allows measurement of wood moisture content between 6 % and 60 % (Otten *et al*., 2017). The moisture content of the wood was determined as usual in wood technology (the ratio between the weight of water and the weight of the wood in an absolutely dry state, expressed in %).

Wood degradation was assessed using an IML PD500 resistograph (IML Instrumenta Mechanik Labour System GmbH, Wiesloch, Germany) based on the recording of the drilling resistance. A hole was drilled into the wood with a tiny drill with a diameter of 2 mm and the resistance of the material to drilling was recorded. The method is based on the fact that less energy is needed to drill a hole in decayed wood than in sound wood. If the device does not record the resistance, the wood is heavily decomposed (Sharapov *et al*., 2019). Alternatively, non-recording of the drilling resistance could also be the result of cracks, holes or other voids.

The mechanical properties of the wood were determined non-destructively. The speed of sound was determined using a device manufactured by Fakopp Microsecond timber. Two electrodes were driven into the wood at a distance of 500 mm. Then the emitting electrode was tapped with a 100 g steel hammer and the transit time of the sound was determined. From the distance and time, the sound transmission was determined. Based on the wood density and sound transmission data, the dynamic modulus of elasticity was calculated according to Eq. 1.

$$dMoE = \rho \times v^2 \qquad (1)$$

Where:
dMoE – dynamic modulus of elasticity, MPa,
v – sound velocity, m/s
ρ – density, kg/m^3.

It should be noted that the dynamic modulus of elasticity is, as a rule, consistently higher than the static modulus. Dynamic determination of the modulus of elasticity, compared to static determination, usually gives about 10 % to 20 % higher values (Chauhan and Sethy, 2016). Measurements were performed on the areas without cracks, knots and growth anomalies with parallel fibre orientation.

At selected sites, density was determined indirectly by the screw withdrawal technique. A screw with a diameter of 3 mm and a depth of 15 mm was screwed into the wood with a screwdriver. The maximum force required to extract the screw was determined using a Screw Withdrawal Resistance Meter (Fakopp Enterprise Bt). The screw extraction force correlates well with the mechanical properties and is a good indicator of the initial, invisible stages of decay (Xue *et al.*, 2019).

In addition, four samples were isolated from the mill at representative locations, as presented in Table 1. These samples were examined in detail in the laboratory, as described below. Microscopic analysis was performed using an Olympus DSX1000 digital microscope (Olympus, Tokyo, Japan). The surface area and cross-section of the selected samples were analysed. Before the microscopic analysis, the transverse xylotome plane was prepared using a GSL 1 sliding microtome (Künten, Switzerland). The analysis was performed under mixed illumination (light and dark field).

Wood density was determined using a GeoPyc device (Micrometics, Norcross, USA), which allows accurate volume measurement with a dry, flowable medium made of a mixture of very small graphite particles and ceramic microspheres. The oven-dry mass of the samples was determined before the measurement. The measurements were performed on absolutely dry wood, as the system is best suited for determining the density of wood in the absolutely dry state, where the moisture content of the sample does not change (Arnič *et al.*, 2021; Humar *et al.*, 2022).

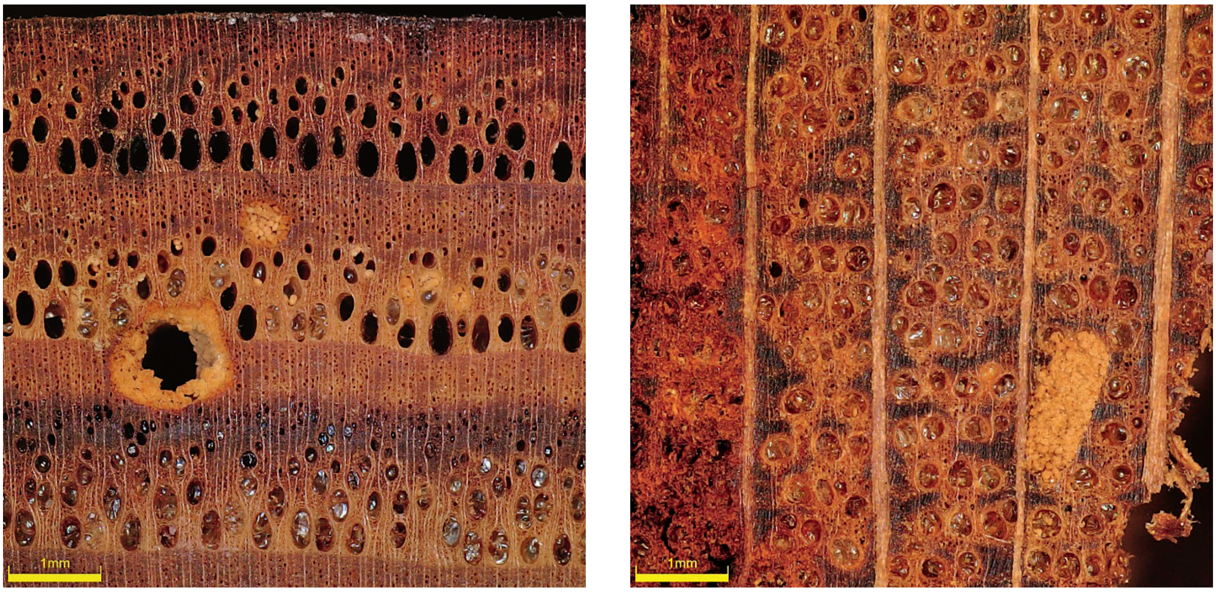
Quantitative elemental analysis was also performed on isolated samples. The inorganic elemental content of the samples was determined using an XRF TwinX X-ray fluorescence spectrometer manufactured by Oxford instruments (Abingdon, UK). Measurements were performed with a PIN detector (U = 26 kV, I = 112 µA, t = 360 s).

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Microscopic analysis revealed that the mill in question consists predominantly of sweet chestnut (*C. sativa*) and European white oak (*Quercus sp.*) (Figure 2). The ring-porous structure is clearly visible in the images (Figure 2). The presence of the wide parenchyma rays distinguishes the oak from the sweet chestnut (Wagenführ, 2014).

The use of chestnut and oak wood in the construction of the mills indicates that part of the local population was aware of the importance of the use of durable wood species in harsh conditions with high relative humidity. Chestnut and oak wood are known for their durability and resistance to fungal decay (Brischke *et al.*, 2013). This made them an ideal material for building the mills and ensured that the structure would last for many decades.

The assessment of the timber in the mill was carried out in November 2022. The outside temperature at the time of the visit was 13 °C, and the relative humidity was between 75 % and 85 %. It should be noted that the mill is located near running water, so high relative humidity is to be expected. The high relative humidity resulted in a relatively high moisture content (*MC*) of the wood (Figure 3). The *MC* of the object varied be-



A) B)

Figure 2 Cross-section of sweet chestnut (*C. sativa*) (A) and oak (*Quercus* spp.) wood sample (B); cross-section holes are caused by insect damage
Slika 2. Poprečni presjek uzorka pitomog kestena (*C. sativa*) (A) i hrasta (*Quercus* spp.) (B). Rupe na poprečnom presjeku oštećenja su nastala djelovanjem insekata.

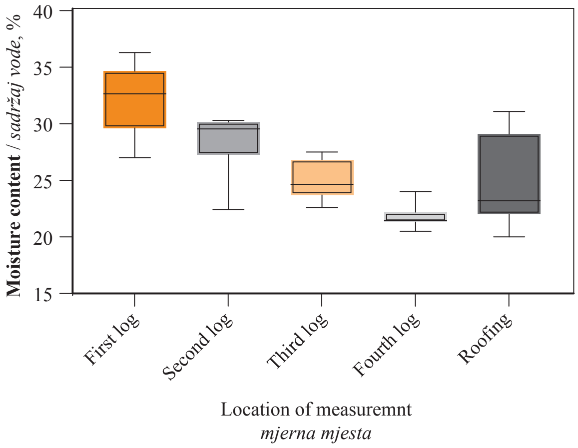


Figure 3 Wood moisture content at various locations in water mill (n = 10)
Slika 3. Sadržaj vode u drvu na različitim mjestima u vodenome mlinu (n = 10)

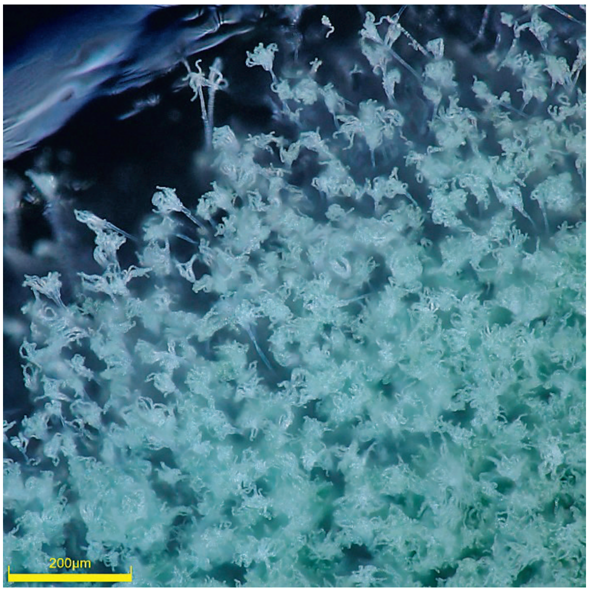


Figure 4 Fungal conidia that developed from collected spores belonging to genus *Penicillium*
Slika 4. Konidije gljivica koje su se razvile iz nakupina spora roda *Penicillium*

tween 20.0 % and 36.3 %. The highest individual and average moisture content was determined on the log that was adjacent to the ground and thus exposed to splash water. The average *MC* decreased with increasing distance from the ground. Relatively high *MC* was determined on the roof elements caused by roof leakage. Although the roofing was still not degraded.

The key question in connection with *MC* is: What is the limiting *MC* for fungal decay? Fungi can decompose wood if the *MC* is above a certain limit. A wide range of data is available in the literature. The first set of data states that the limits of *MC* depend primarily on the fungal species. For example, Schmidt (Schmidt, 2006) reported that the minimum *MC* of wood varies between (30 %) (*Fibriporia vaillantii* (DC.) Parmasto and *Gloeophyllum trabeum* (Pers.) Murrill) and 25 % (*Coniophora puteana* (Shum.: Fr.) P. Karst and *Serpula lacrymans* (Wulfen) P.Karst). However, new data indicate that *MC* limits for fungal growth also depend on the fungal species and wood species. For example, the limit *MC* for the decay of *G. trabeum* on Scoots pine sapwood is 16 %. However, it should be borne in mind that such low-limit values are only possible if the water source is nearby. On the other hand, the limiting moisture content of oak wood varies between 23.0 % (*Coniophora puteana*) and 33.8 % (*Trametes versicolor*) (Meyer and Brischke, 2015). Unfortunately, limit *MC* data are not available for sweet chestnut wood. As can be seen in Figure 3, the *MC* in the respective mill is above the threshold value in several places. It was found that the critical dose (number of days with *MC* suitable for wood decay) corresponding to incipient decay can be seen as more or less independent of the wood species. The critical dose was found to be around 325 days with favourable conditions for fungal decay (Isaksson *et al*., 2013).

One of the prerequisites for fungal infestation is the presence of fungal spores. Therefore, the spore concentration in the mill (1625 CFU/m^3) and before the mill (3480 CFU/m^3) was determined. Usually, between 360 and 1230 CFU/m^3 are reported in the air (Flores *et al*., 2014). As higher values are reported in the vicinity of the mill, this indicates the potential of the fungus in the environment. From the microscopic analysis, it can be concluded that the majority of the colonies identified belong to the genus *Penicillium* (Figure 4). *Penicillium* is a genus of ascomycetous fungi that is part of the mycobiome of several species and is of great importance in the natural environment.

However, in addition to moulds, wood-destroying fungi have also been identified. Secondary mycelium with clamps was found in the vessels of oak wood (Figure 5A). This type of mycelium is characteristic of basidiomycetes, which usually cause decay of wood (Schmidt, 2006). In addition, pink slime moulds were present on the wood surface (Figure 5B). These fungi typically occur on surfaces in high relative humidity environments (Eaton and Hale, 1993).

The outer part of the logs exposed to weathering was grey (Figure 1). Loose cellulose fibres can be seen on the microscopic image. The surface of the wood absorbs light due to the presence of lignin. As a result of UV irradiation, the lignin is degraded and leached from the surface layers. Loose cellulose fibres remain on the surface resulting in the silver-grey colour of weathered wood (Kropat *et al*., 2020). No blue colouration was observed in oak and sweet chestnut wood. The presence of extractives seems to limit the growth of blue stain fungi on the wood surface (Vek *et al*., 2019).

The density of the wood corresponded to the information found in literature. The average density of

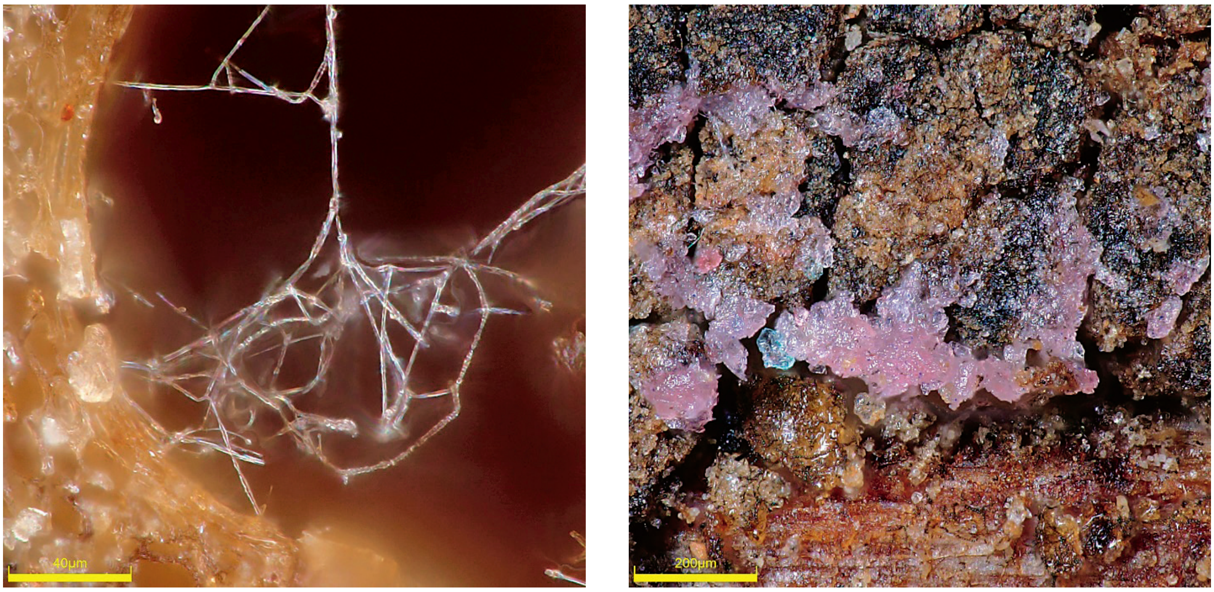


Figure 5 Secondary, clamp fungal mycelium in oak wood vessel (A) and slime fungus growing on wood surface (B)
Slika 5. Sekundarni micelij stezaljke u traheidi hrastovine (A) i sluzava gljiva koja raste na površini drva (B)

Figure 6 Presence of loose cellulose fibres on weathered wood surface
Slika 6. Gubitak celuloznih vlakana na površini drva izloženoga vremenskim utjecajima

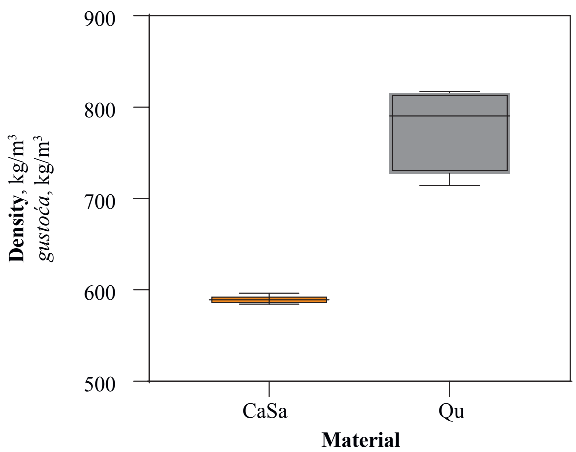


Figure 7 Density of mill sweet chestnut (CaSa) and oak (Qu) wood determined in laboratory (n = 5)
Slika 7. Laboratorijski određena gustoća drva pitomog kestena (CaSa) i drva hrasta (Qu) od kojih je mlin izgrađen (n = 5)

oak logs was 778 kg/m^3, while the density of sweet chestnut was slightly lower (590 kg/m^3). These values are in agreement with the literature data for both species. The literature shows that the density of oak varies between 390 kg/m^3 and 930 kg/m^3 (Wagenführ, 2014). A high density indicates that the wood has not been degraded. Furthermore, it is generally assumed that density has a positive influence on durability within the same ring-porous species. Denser wood is more durable than wood with lower density (Brischke *et al.*, 2013). The density determined in the laboratory agrees with the density determined during screw withdrawal (787 kg/m^3). This evaluation proves that only high-quality material was used for the respective construction. The high quality of the wood is reflected in the dynamic modulus of elasticity (*dMoE*). The dynamic modulus of elasticity was only determined on oak logs. The average *dMoE* of oak logs was 14.0 GPa. This is consistent with literature data for the static *MoE* of oak logs, which range from 10.0 GPa to 13.2 GPa. As mentioned earlier, the *dMoE* is always higher than the static *MoE* (Chauhan and Sethy, 2016). This is evidence of good structural integrity of the logs in the studied work.

The analysis of the wood with the resistograph confirmed previous studies. Twenty-six resistograph measurements were taken. Signs of rot were only found

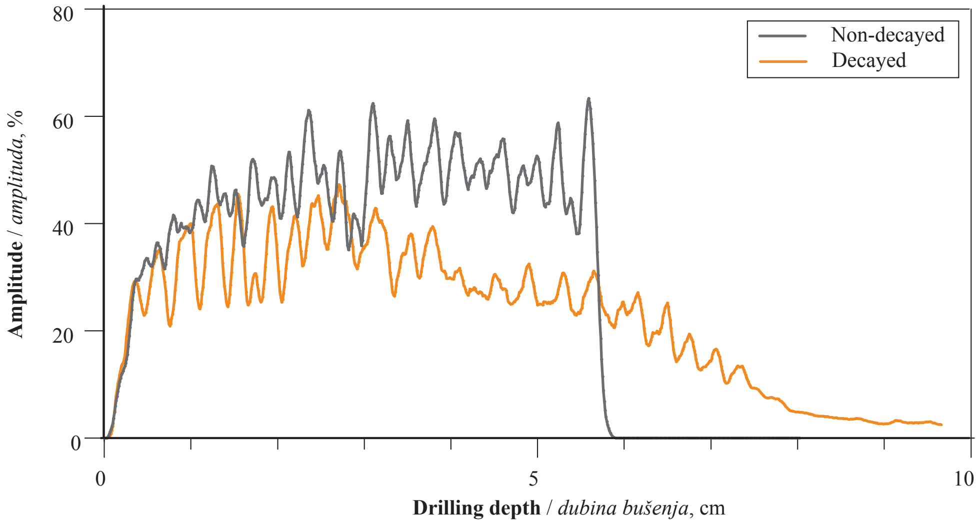


Figure 8 Resistograph profiles of non-decayed and decayed beam in the analysed mill
Slika 8. Profili rezistografa neraspadnute i raspadnute grede u analiziranome mlinu

at one point in the roof structure. This is consistent with the measurements of *MC* and is probably a result of roof leakage. The logs were not decayed. Only the outer surface was partially softened, probably due to weathering (Figure 8). The outer part of the logs was partially degraded due to the presence of the less durable sapwood, which was partially degraded by beetles of the genus *Anobium* (Figure 9). *Anobium* beetles are common in old constructions of wet hardwood (Unger *et al*., 2001).

Insect galleries were mainly found on the outside of the structure. The interior was at least partially protected by smoke deposits. The chimney without a flue was located inside the mill. The smoke could therefore easily spread over the entire volume of the building and escape through the opening in the roof. It should be remembered that the mills also operated at night, so the fire was the source of light and heat. Rahmat and coworkers (2020) reported that condensed gases from wood burning have fungicidal effect. As can be seen from the XRF spectra of the corresponding deposits, they contain high concentrations of iron (Fe), sulphur (S), chlorine (Cl), cadmium (Cd) and manganese (Mn). These elements are assumed to have originated from the corrosion of metal roof and smoke (Humar, 2010). However, it should be noted that these deposits were present only on the interior side of the beams.

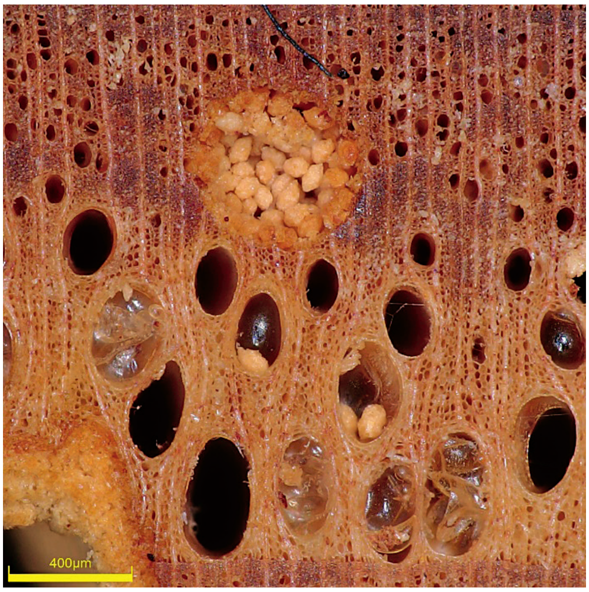


Figure 9 Insect hole in sweet chestnut wood filled with debris typical for beetles from genus *Anobium*
Slika 9. Rupe od kukaca u drvu pitomog kestena ispunjene ostatcima tipičnima za kornjaše iz roda *Anobium*

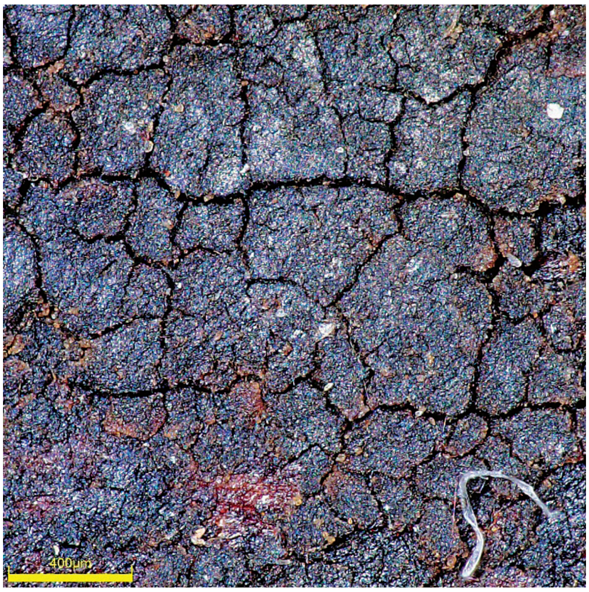


Figure 10 Deposits on oak beams surface in mill interior
Slika 10. Naslage na površini hrastovih greda u unutrašnjosti mlina

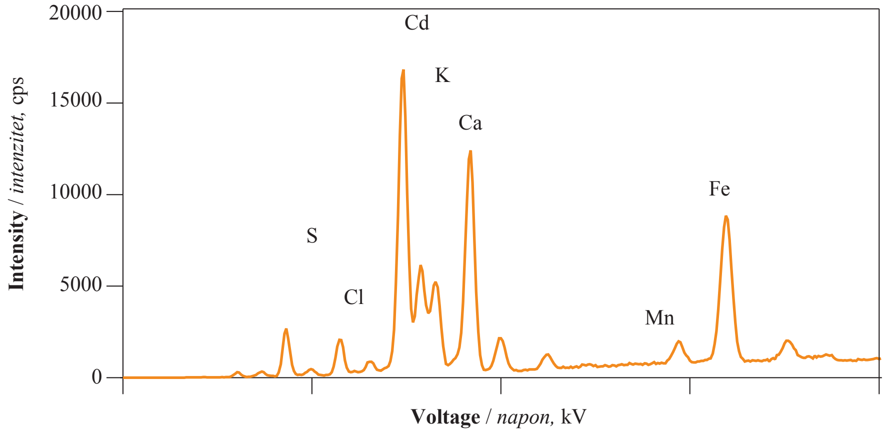


Figure 11 Representative XRF spectra of wood from mill interior
Slika 11. Reprezentativni XRF spektri drva iz unutrašnjosti mlina

4 CONCLUSIONS
4. ZAKLJUČAK

The oak and sweet chestnut wood in the mill examined is in quite good condition, as revealed by microscopic and mechanical analysis. The decay is limited to the sapwood and some other exposed elements. The main reason for the good condition of the respective building is the use of durable wood species and good construction. Respective mills offer a great opportunity to monitor the performance of wood in a realistic environment. To protect the respective mills for future generations, the roof should be maintained regularly to avoid possible leaks. The respective mill confirms that wooden structures can last for decades if proper wood is selected for the application, and protection by design measures is fully considered.

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