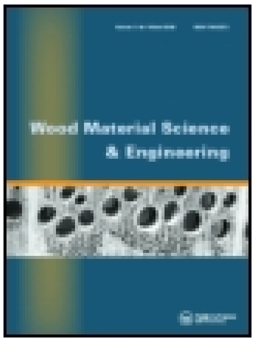

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ORIGINAL ARTICLE

Performance of wood in the Franja partisan hospital

Davor Kržišnik[a], Christian Brischke[b], Boštjan Lesar[a], Nejc Thaler[a] and Miha Humar[a]

[a]Department of Wood Science and Technology, University of Ljubljana, Ljubljana, Slovenia; [b]Department Wood Biology and Wood Products, University of Goettingen, Goettingen, Germany

ABSTRACT
Wood is one of the most important construction materials and its use in building applications has further expanded in recent decades. In order to enable even more extensive and reliable use of wood, factors affecting wood's service life need to be understood. It is well known that fungal degradation of wood is predominantly affected by moisture content (*MC*) and temperature (*T*). In order to elucidate the influence of these two factors, long-term monitoring of *T*, relative humidity (*RH*) and wood *MC* was carried out at the WWII partisan hospital Franja, Slovenia. The results clearly showed that fungal degradation of wood is influenced by *MC* and *T*. A model to predict brown and white/soft rot decay of wood was applied to predict the expected service lives of different building components of the hospital cabins. The predicted times until onset of decay were well in accordance with findings made during visual assessments and drill resistance measurements at this historical site. The monitoring concept in combination with a mathematical decay prediction model can provide accurate data and valuable guidance for building modern structures and maintaining the cultural heritage.

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Water; moisture; service life; degradation; buildings; wood decay fungi

1. Introduction

The expected service life of wooden structures under given exposure conditions is a key issue in the selection of materials for construction. The time during which a particular wooden structure will fulfil its function depends on a variety of factors such as wood moisture, temperature, wood species and pH value. (Isaksson and Thelandersson 2013). However, wood-degrading fungi (brown-rot, white-rot and soft-rot fungi) predominantly affect the service life of wood exposed indoors and outdoors (Van den Bulcke *et al.* 2011). In addition to a material's inherent durability, the moisture and temperature conditions inside the wood, i.e. the material climate, are the most important factors influencing the ability of fungi to decompose wood (Schmidt 2006, Brischke *et al.* 2008, Van Acker *et al.* 2014). These two factors are influenced by the design of the construction, the exposure conditions and local climatic conditions (micro-climate). If moisture content (*MC*) and temperature (*T*) are monitored, the severity of a particular location can be evaluated (Welzbacher *et al.* 2009). Based on the severity of the location, additional protection can be applied through design measures. However, if this is not sufficient or possible, a more durable material should be used. Durable materials can be chosen from the group of naturally durable wood species (limited number of species in Europe), wood treated with biocides or modified wood (Kutnik *et al.* 2014).

The micro and material-climatic conditions at a particular location need to be assessed with respect to the physiological needs of wood-destroying fungi enabling wood decay. Numerous studies have focused on determining *T* and *MC* thresholds for fungal growth and decay. The ability of fungi to degrade wood is frequently associated with their ability to release low molecular agents and extracellular enzymes and their transport into the cell wall, which is assumed to require liquid water. The fibre saturation point (*FSP*) of wood is therefore usually assumed to be the threshold for fungal decay. Experimental investigations by several authors have confirmed this assumption, e.g. Schmidt (2006), who reported that the minimum *MC* of wood for the growth of *Fibriporia vaillantii* and *Gloeophyllum trabeum* was 30%, while the minimum *MC* of *Coniophora puteana* and *Serpula lacrymans* was slightly lower (26%). Moisture limits for fungal growth and decay depend on the fungal species in question (Huckfeldt 2003), and differ considerably among wood species (e.g. Meyer and Brischke 2015). More recently, various authors have reported test results indicating that some wood-destroying fungi might also be able to degrade wood below fibre saturation (Meyer *et al.* 2016, Brischke *et al.* 2017). Höpken (2015) showed for piled wood samples of Scots pine sapwood (*Pinus sylvestris*) and English oak (*Quercus robur*, sap- and heartwood) and the brown-rot fungi *C. puteana* and *S. lacrymans* and the white-rot species *Donkioporia expansa* that fungi were able to transport water from the water source agar in the Erlenmeyer flasks to the piles and within them and subsequently to colonize wood from 15.1% to 21.8% moisture content. Samples were degraded even at only 17.9% moisture content (*D. expansa*, oak heartwood). In addition, Stienen *et al.* (2014) showed for *Antrodia xantha* the colonization of *P. sylvestris* sapwood with only 17.4% moisture content and decay at 24.6%,

CONTACT Miha Humar ✉ miha.humar@bf.uni-lj.si Department of Wood Science and Technology, University of Ljubljana, Ljubljana SI-1000, Slovenia

which agrees with earlier studies showing that fungal decay occurred at a relative humidity (*RH*) significantly below 100% (e.g. Bavendamm and Reichelt 1938, Ammer 1963).

Service life prediction of timber structures is an important task not only for new buildings and commodities but also for historic structures, particularly with respect to restoration and for identifying the need for preservation measures. A variety of models have been developed with the aim of predicting fungal decay based on different climate-related parameters (Brischke and Thelandersson 2014). Data from laboratory tests with monocultures of basidiomycetes have been used (e.g. Viitanen *et al.* 2010a), as well as long-term field tests at climatically different locations (e.g. Isaksson *et al.* 2013). Acquisition and processing of data can be very different but the modelling itself is frequently based on a dosimeter approach, considering fungal decay as a response to a dose that is a function of the material-climatic parameters *T* and *MC*. In addition to exposure-related impact factors, the material resistance of wood products can be modelled on analogy based on a dose–response relationship as shown by Meyer-Veltrup *et al.* (2017).

This study aimed at monitoring the micro and material climate outside and inside a wooden structure of the partisan hospital Franja, Slovenia. Differences in the moisture- and temperature-induced risk of fungal decay were modelled and the effectiveness of the preservative treatment was evaluated seven years after a major flood event and subsequent restoration. These data are important from other perspectives. The importance of wood in construction applications is increasing. Wood and wood-based composites is more and more frequently used for multi-storey buildings. Moisture monitoring in these kinds of buildings is becoming important, in order to control possible leakage and lack of maintenance as this pose threat for all users.

2. Material and methods

2.1. Partisan hospital Franja

Monitoring was performed at the WWII partisan hospital Franja, Slovenia, which consists of 14 wooden barracks. Detailed monitoring was performed in the so-called cabin for the wounded at this hospital (http://www.muzej-idrija-cerkno.si) (Figure 1). The hospital is situated in a remote location in Pasice gorge near Cerkno (GPS location; 46.154081, 14.028197), approximately 600 m above sea level. Since the stream in the gorge is present during all seasons, the relative humidity is always very high. The majority of the huts were completely renovated in 2010 after a disastrous flood in September 2007. The design of the hospital is the same as it was during WWII. All huts were designed as temporary shelters, and subsequently declared a cultural monument of national importance. The cabins are made primarily of Norway spruce (*Picea abies*). Since the climatic conditions in the gorge are fairly harsh, all the Norway spruce wood was dip treated with a copper-ethanolamine-based wood preservative (Cu-EA) (Silvanolin®, Silvaprodukt, Ljubljana, Slovenia). This product consists of copper hydroxide/carbonate, ethanolamine, boric acid and quaternary ammonium compounds. Details about the impregnation procedure are not known. It is likely that the impregnation procedure was not performed correctly, so considerable decay occurred at several points. Components that were subject to monitoring were assigned to use classes according to EN 335 (2013) as follows: UC 1 – Interior, dry; UC 2 – Interior or under roof, not exposed to weather, possibility of condensation; UC 3 – Exterior, without soil contact, exposed to weather; UC 3.1 limited moist conditions; UC 3.2 – persistently moist conditions; and UC 4 – Exterior, in contact with soil or fresh-water.

Figure 1. Cabin for the wounded at the WWII partisan hospital franja. Measurements were performed in the cellar (bunker) below the cabin, on the façade facing the hill, and on the first floor.

2.2. Assessment of decay

Decay in the bunker was assessed visually, using a knife for picking into the wood. In addition, decay was quantified through resistograph measurements (PD 500, IML, Moultonborough, USA). The resistograph analysis was performed in June 2016. A resistograph is an electronic high-resolution needle drill resistance measurement device. A thin, long steel needle is driven into the wood. While drilling, the required energy is measured in dependence on the drilling depth of the needle. Resistograph devices are different from other resistance drills in that they provide a high linear correlation between the measured values and the density of the penetrated wood. Even interior decay can thus be easily detected. A drilling needle of 1.5 mm diameter with a diameter of needle tip of 3.0 mm was used. Resistograph measurements were performed on all wood elements in the cabin of bigger diameter. Planks were visually inspected only.

2.3. Monitoring types and equipment

Continuous monitoring of temperature (*T*), relative humidity (*RH*) and wood moisture content (*MC*) was performed at the micro-locations described in Table 1. Temperature sensors (Scanntronik Mugrauer GmbH, Zorneding, Germany) were used to obtain exact values for the conversion of electrical conductivity into wood *MC* (Otten *et al.* 2017). Temperature was monitored in the cellar and on the outer façade facing east (hillwards). Temperature data were collected twice per day using Thermofox data loggers (Scanntronik Mugrauer GmbH). In addition, *T* and *RH* data were recorded hourly with a Thermofox Hygrofox sensor. *RH* and *T* were determined in the attic and in the cellar of the cabin. The attic was well ventilated, so the monitored climate was assumed to reflect the surrounding climate well. Due to the harsh conditions, the sensor in the cellar failed fairly soon.

Wood *MC* was determined at eight locations in and outside the cabin (Table 1) every 12 hours for a total period of approximately 3 years. Insulated electrodes (stainless steel screws) were installed at different positions and depths and connected to the extension module (Gigamodule, Scanntronik Mugrauer GmbH) for measuring the electrical resistance (Žlahtič Zupanc *et al.* 2017). The measurement system applied enables sufficiently accurate measurements of between approximately 6% and 90% *MC* (Otten *et al.* 2017).

Table 1. Location of structural members for moisture content (MC) measurements in the cabin for the wounded. Use classes were assigned according to EN 335 (2013). All elements were made from Cu-EA treated Norway spruce.

No.	Description	Use class
F1	Cellar: vertical plank covered with soil on one side	4
F2	Cellar: horizontal plank; part of the ceiling/floor	3.2–4
F3	Cellar: beam; part of the ceiling	3.2
F4	Cellar: vertical plank	3.2–4
F5	1st floor: pillar; 1.8 m above the floor; indoors	1
F6	1st floor: pillar; 0.5 m above the floor; indoors	1
F7	Façade: corner board; 1.8 m above ground	3.1
F8	Façade: boards above the door	3.1

The measuring and logging equipment was placed inside a steel box located in the building so as to be protected from wetting and vandalism. Wood species-specific resistance characteristics were used to translate electrical resistance into wood *MC* according to the methodology described by Otten *et al.* (2017). The data were periodically downloaded to a personal computer and analysed with Scanntronik software SoftFOX and MS Excel. The systems were also periodically checked, and batteries were replaced when necessary. In total, almost 17,500 *MC*, 14,000 *RH* and 18,000 *T* measurements were collected. Data gaps occasionally occurred due to malfunction of the loggers or batteries. Because Franja was not accessible during winter, batteries and loggers could not be checked for several months per year. Eighty per cent of the *T* and 70% of the *MC* measurements were recorded in the period between September 2014 and October 2017. In October 2017, monitoring was terminated due to the renovation of the buildings.

2.4. Dose–response model

Finally, a dose–response model for the fungal decay of wood in aboveground situations, as described in detail by Brischke and Meyer-Veltrup (2016) and shown in Figure 2, was applied to the recorded material-climatic data (*MC, T*). For comparative analysis, the total dose *D* (=cumulated daily dose *d* over time) was determined. A moisture-induced dose component d_{MC} and a temperature-induced dose component d_T were therefore calculated based on the physiological needs of decay fungi and optimized on the basis of long-term field tests at several climatically different locations in Europe by Brischke and Rapp (2008). The model considers wood *MC* and *T* as the key parameters for fungal growth and decay and allows a daily dose between zero for adverse conditions and one for favorable conditions. The two-dose components

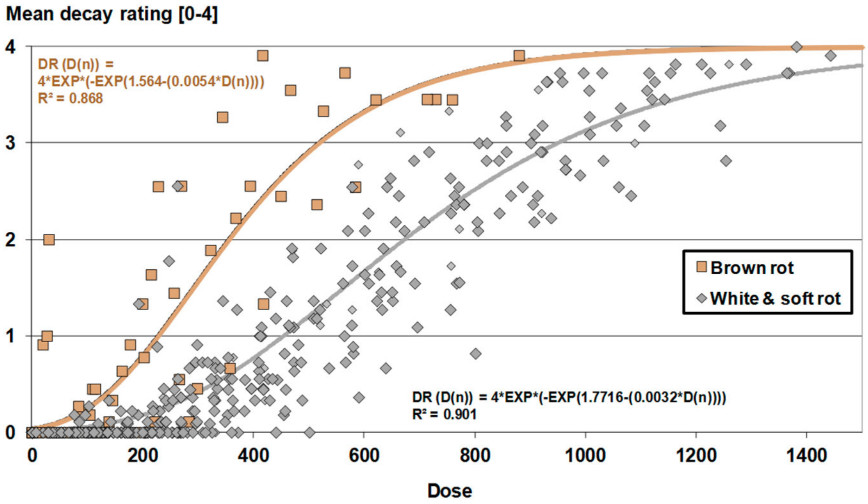

Figure 2. Relationship between dose *D* and the mean decay rating according to EN 252 (2015) of various softwood specimens exposed at climatically different test sites in Europe (each dot represents the mean decay rating for one wood species at one exposure site at a certain time of exposure; diamonds and grey line: decay was dominated by white and soft rot, squares and brown line; decay dominated by brown rot), modified after Brischke and Meyer-Veltrup (2016).

d_{MC} and d_T are calculated separately as follows:

$$d_{MC} = 6.75 \times 10^{-10}MC^5 - 3.50 \times 10^{-7}MC^4 + 7.18 \times 10^{-5}MC^3 - 7.22 \times 10^{-3}MC^2 + 0.34MC - 4.98; \quad \text{if } MC \geq 25\% \tag{1}$$

$$d_T = 1.8 \times 10^{-6}T^4 + 9.57 \times 10^{-5}T^3 - 1.55 \times 10^{-3}T^2 + 4.17 \times 10^{-2}T; \quad \text{if } 40^\circ C \quad \langle T \rangle - 1^\circ C \tag{2}$$

where d_{MC} is the MC induced daily dose (d), d_T is the temperature-induced daily dose (d), MC is the daily wood moisture content (%) and T is the daily average wood temperature (°C).

To consider the differently severe impact of MC and temperature on decay, a weighting factor a was added to calculate the daily dose d as follows. The following side conditions were considered: the daily dose d of days with a temperature above 40°C, with a temperature below −1°C, or with an MC below 25% was set as zero:

$$d = ((a \times d_T) + d_{MC})/(\text{a} + 1); \quad \text{if } d_T > 0 \text{ and } d_{MC} > 0, \tag{3}$$

where d is the daily dose (d) and $a = 3.2$ is the weighting factor of the temperature-induced daily dose component d_T.

For n days of exposure, the total dose is given by

$$d(n) = \sum_{1}^{n} d_i = \sum_{1}^{n} (f(d_T(T_i), d_{MC}(MC_i))) \tag{4}$$

where T_i is the average temperature (°C) and MC_i is the average moisture content for day i (%).

Decay is initiated when the accumulated dose reaches a critical dose. The dose is thus defined as a material-climate index and the response is considered to be the mean decay rating according to EN 252 (2015). Service lives were estimated according to Equation (5) and Figure 2 using a mean decay rating of two (= moderate decay) as the limit state. Any decay rating above this limit state means that serviceability is no longer given. A critical dose $d_{\text{crit}} = 670$ (for white and soft rot) and $d_{\text{crit}} = 356$ (for brown rot) was needed to reach the limit state. Service lives were consequently estimated separately for a combination of white and soft rot, and for brown rot using a critical dose $d_{\text{crit}} = 670$ and 356, respectively, as follows:

$$ESL = \frac{d_{\text{crit}}}{d_a}, \tag{5}$$

where ESL is the expected service life (a), d_{crit} is the critical dose (d) and d_a is the annual dose (d).

The annual dose d_a was calculated as an average of several years to consider, on the one hand, climatic differences between years and, on the other hand, the potential increase in the wetting ability of wood during long-term outdoor exposure.

2.5. Retention analysis

The quality of a wood preservative treatment is determined by the penetration and retention of active ingredients (EN 351-1, 2007). In order to elucidate these parameters, outer layers of the selected poles were carefully removed with a knife and axe. Sections of each layer were milled together in an SM 2000 Retsch mill (Retsch GmbH, Haan, Germany) and three parallel tablets ($r = 16$ mm; $d = 5$ mm) were pressed from the milled material with a Chemplex Spectro pellet press (Chemplex Industries Inc., Palm City, USA). The copper and chromium contents in the tablets were determined with a Twin-X XRF spectrometer (XRF Twin-X, Oxford Instruments, Abingdon, UK). Measurements were performed with a PIN detector ($U = 26$ kV, $I = 112$ μA, $t = 360$ s).

3. Results and discussion

3.1. Assessment of decay

The hospital was inspected for the first time in 2014, four years after opening, due to reports of severe decay and the formation of fruiting bodies developed in the bunker. Visual inspection revealed that staining fungi often developed, as well as fruiting bodies and mycelia belonging to *Antrodia* sp., *Fomitopsis* sp., *Coniophora* sp., *Schizophyllum commune* and others (Figure 3)(Jann, 1990). Fungal fruiting bodies, mycelia and decay were detected in the cellar only. In the above ground structures and on the façade, neither decay nor other signs of fungal growth were found.

In June 2016, decay was quantified with resistograph measurements only on structural elements that were thick enough for measurements. The thinner planks were only assessed visually. In total, 43 wooden columns and 17 wooden beams were analysed in the cellar. All elements were made of Norway spruce wood and were round, with an average diameter of 18 cm. They were dip treated with a copper-ethanolamine-based wood preservative (Silvanolin®, Silvaprodukt). Copper retentions in the outer 5 mm were between 1200 and 1500 ppm. Copper did not penetrate deeper than 5 mm. In order to achieve sufficient protection in such a harsh environment, penetration of at least 20 mm is required, and the copper concentration should exceed

Figure 3. Mycelia of *Antrodia sp.* growing on the surface of wood in the cellar.

4000 ppm (Humar *et al.* 2016). Insufficient copper retention enables the growth of copper tolerant fungi such as *Antrodia* (Schmidt and Moreth 1996; Humar *et al.* 2002), as well as other decay fungi.

Resistograph analysis revealed that, on average, 40% of the cross-section of the analysed wood elements were degraded. Sound elements without any signs of decay were found only near the doors, where air circulation was possible. On the majority of the analysed wood columns, decay had developed in the interior. Only 6 of the 60 analysed elements were free of decay (Figure 4).

In addition to the beams, clear signs of decay were detected in particular on vertical planks after 4 years of exposure, when the monitoring started. In contrast, the horizontally exposed planks that were part of the ceiling showed fungal decay not before the seventh year after construction. No visible signs of decay after seven years of exposure were found in the interior of the first floor of the cabin and on its outer facade.

3.2. Temperature monitoring

Temperature is one of the most important factors affecting wood's service life. Extreme temperatures can affect fungal vitality. In general, the minimum temperature for fungal growth and degradation is usually close to 0°C, since there is no liquid water available for fungal metabolism below freezing point. The optimum temperatures for most decay fungi are between 20°C and 30°C. The maximum for mycelial growth and wood degradation by most wood fungi is generally between 40°C and 50°C, because at higher temperatures, proteins (enzymes) start denaturing (Schmidt, 2006). Considerable differences exist in temperature optima and limits between species and even between different isolates of the same species (Schmidt, 2006). However, when interpreting the temperature data from this case study, it should be noted that the temperature was measured at one or two locations only, although the temperature at micro-locations can differ greatly, as for instance indicated by Gobakken *et al.* (2008), who monitored wooden huts in Svalbard, Norway.

As can be seen from Table 2, the temperature in almost all locations was favourable for fungal growth during most of the year. Only a few months during the winter 2016/2017 were extraordinarily cold and thus did not allow fungal activity. The average temperature was fairly uniform at all micro-locations. Average temperatures in the façade were slightly higher during the summer months and, in contrast, slightly lower in the winter months compared to those in the bunker. Temperatures in the attic were similar to those on the surface of the façade. The highest maximum summer temperature was determined on the façade in July 2016 (26.3°C), which is relatively cold compared, for instance, to the capital city Ljubljana, where temperatures were approximately 10°C higher. The low maximum temperature at the hospital is due to Franja being located in a gorge with only one hour of direct sunlight per day. As an analogy, extreme winter temperatures are also lower compared to several places near Franja. The lowest winter temperature of −10°C was determined in the attic of the cabin in January 2017.

3.3. Monitoring of relative humidity (RH)

Relative air humidity is another factor that has a considerable influence on the performance of wood, to a higher extent

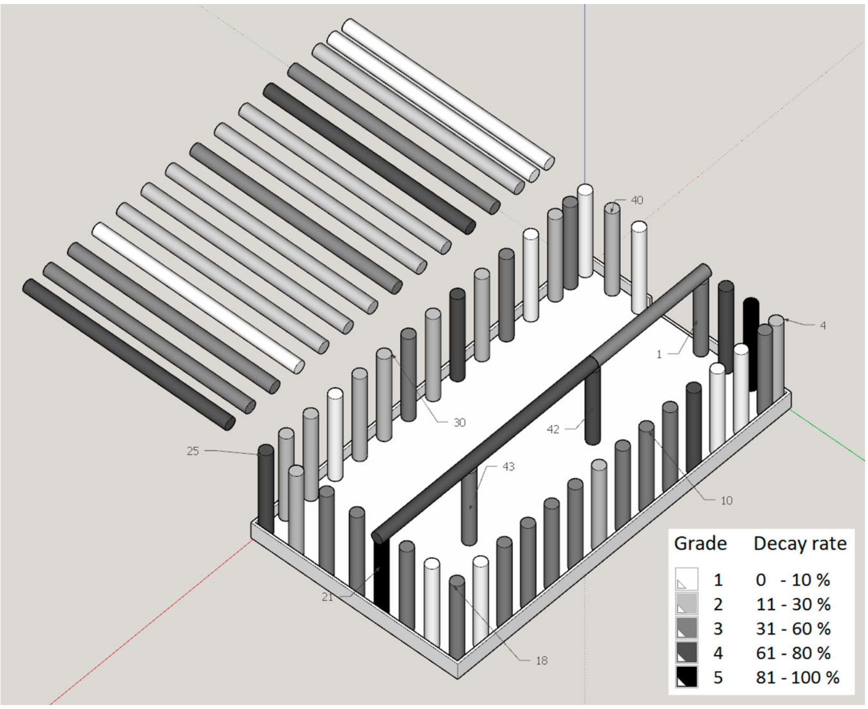

Figure 4. Graphic presentation of decay in columns and beams in the bunker of the cabin for wounded. Decay rate was determined with a resistograph and expressed as a percentage of the degraded cross-section.

Table 2. Average temperatures at different positions of the cabin for the wounded at Franja partisan hospital (data gaps are due to malfunction of data logger or batteries).

		Average temperature (°C)		
Year	Month	Bunker	Façade	Attic
2014	Sep	12.7	12.9	-
	Oct	12.6	12.2	-
	Nov	3.5	1.6	-
	Dec	3.1	1.5	-
2015	Jan	2.9	2.8	-
	Feb	5.1	5.0	-
	Mar	6.2	7.6	-
	Apr	8.2	10.7	-
	May	11.6	13.8	-
	Jun	14.6	17.3	-
	Jul	18.0	20.7	-
	Aug	17.9	20.7	-
2016	Apr	9.4	9.1	9.1
	May	10.0	12.2	12.2
	Jun	14.4	16.6	16.2
	Jul	16.9	19.7	19.2
	Aug	16.1	17.9	17.8
	Sep	15.1	16.4	16.2
	Oct	10.0	9.1	9.4
	Nov	6.0	7.4	6.4
	Dec	0.4	2.4	0.8
2017	Jan	−0.3	−3.1	−2.8
	Feb	2.1	2.2	2.7
	Mar	5.7	7.9	7.8
	Apr	8.0	9.9	9.8
	May	10.9	13.8	13.3
	Jun	15.5	19.0	17.8
	Jul	16.6	20.1	18.5
	Aug	18.2	21.4	19.5
	Sep	14.4	15.2	13.1
	Oct	12.3	13.5	11.6

even than temperature. If the wood is dry, fungi cannot degrade it, in spite of optimum temperature. On wood located in conditions with high *RH*, the first staining fungi will occur at an *RH* above 80%, and degradation can occur at even higher values of *RH*, above 90%. However, for severe degradation, water leakage and/or a condensing environment is required.

The average *RH* in the bunker of the cabin was fairly high, i.e. 96.3% (four-month average). Unfortunately, the sensors were not designed to work in such a harsh condensing environment, and they afterwards failed. The *RH* in the attic was slightly lower (Figure 5), i.e. 86%. The lowest, but fluctuating *RH* was measured during the winter months, while average *RH* during summer was fairly constant but significantly higher. In sub-tropical regions, the average *RH* in a house can easily exceed 80%, as for instance described by Du *et al.* (2014) for a house in Chongqing in central China. This indicates that the RH-induced risk in this sub-alpine climate is comparable to a sub-tropical climate. High *RH* values are usually associated with mould and stain problems, and degradation can subsequently occur (Viitanen *et al.* 2010b). High *RH* was thus apparently one of the main reasons for constant problems with mould in Franja, too.

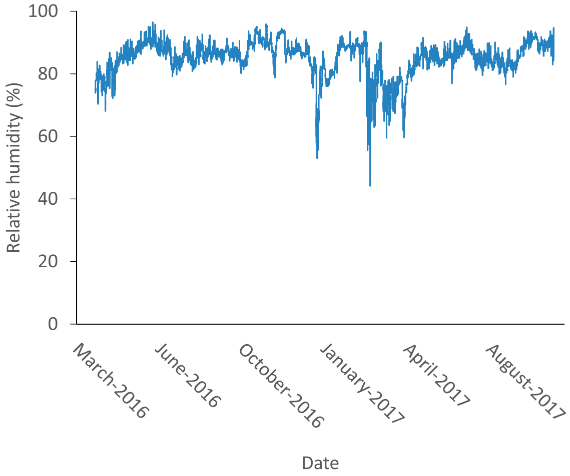

Figure 5. Course of relative humidity in the attic of the cabin for the wounded of franja partisan hospital during the period from March 2016 to October 2017.

3.4. Monitoring of wood moisture content (MC)

As expected, the wood *MC* reflected the micro-climate in the cabin. The highest average *MC*, i.e. 30.2% was determined in the bunker of Franja partisan hospital (Figure 6, F1–F4). The highest *MC* developed in the horizontal wooden planks that formed the wall. In plank F1, the average *MC* was 38.4%, which provides optimal conditions for wood degradation.

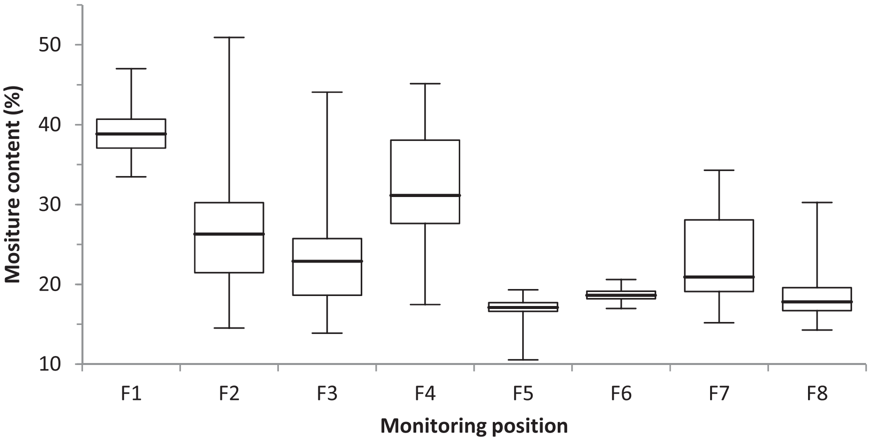

Figure 6. Wood moisture content (*MC*) at different monitoring positions in the WWII partisan hospital franja. The box displays the middle values (25th and 75th percentile), while the whiskers stretch to the greatest and lowest value of that variable. Bold lines indicate the median value.

Table 3. Wood moisture content (MC) data in the monitored cabin. Total number of measurements per monitoring site: 1490.

	Moisture content (%)				Percentage of measurements above threshold *MC*		
No.	Average	Median	Min	Max	20%	25%	30%
F1	38.8	38.7	33.5	47.0	100	100	100
F2	26.6	26.7	14.5	50.9	79	59	28
F3	24.3	23.1	13.9	44.1	71	33	16
F4	32.6	30.7	19.7	45.1	100	93	57
F5	17.1	17.0	10.5	19.3	0	0	0
F6	18.6	18.6	17.0	20.6	2	0	0
F7	22.7	21.0	15.2	34.3	64	35	3
F8	18.5	17.8	14.3	30.3	22	3	0

Aggregated wood *MC* data are presented in Table 3. In addition to average and extreme data, the percentage of wet days, i.e. days when wood *MC* exceeded a particular threshold, are reported. All measurements were performed at least 20 mm below the wood surface. Surface wood *MC* might therefore have been even higher. Different thresholds were taken into account. In general, the 25% *MC* threshold is considered to be the minimum *MC* required for fungal decay of untreated wood, since it represents a conservative *FSP* value, however, lower values are possible if the fungi can transport water from a neighboured moisture source to the wood (Höpken 2015). Fibre saturation is rather a range than a fixed threshold (Popper and Niemz 2009) and varies between 22% and 36%, depending on the wood species.

As can be seen from Table 3, the *MC* of the wood in the bunker was fairly high; even the highest *MC* threshold of 30% was exceeded for long periods. At five out of the eight measurement locations, the *MC* was above 25% for at least 35% of the monitoring time. Apart from plank F1, the wood was neither in ground contact nor was ingress of liquid water due to leakage observed. The high *MCs* were consequently the result of the high *RH* and condensation. The *MC* of the planks on the wall (F1 and F4) of the bunker were higher than 20% all of the time. The *MC* was even higher than 25% for 90% of the monitoring time. Under such harsh environmental conditions, wood needs to be properly preserved to achieve sufficient performance over time.

Surprisingly, the wood *MC* of the façade was also fairly high. The average *MC* of the façade (F7) was 23.4%. The façade faced the hillside and was never exposed to sunlight. The wood therefore took a long time to dry out after rain events or periods of condensation. In contrast, the wooden element that acted as a shelter above the door (F8) was almost completely ventilated, which allowed faster re-drying. Even the wood inside the hut exhibited fairly high *MC*, even though it was not exposed to rain. The average *MC* of the indoor wood was 17.1% (F5) and 18.6% (F6). The higher *MC* was measured in the lower part of the pillars. Although *MC* was rather too low for fungal infestation and decay, it clearly indicated high *RH* in the cabin (Figure 5). However, average *MC* was high enough for fungal decay to spread from the cellar to the upper floor, as reported by Meyer and Brischke (2015) and Höpken (2015), who determined *MC* thresholds for mycelial growth in the presence of an external moisture source. Although Norway spruce is a common species for indoor use, quite different colonisation and degradation values may be obtained on other wood special like oak heartwood.

3.5. Modelling decay risks and predicting service lives

MC and *T* data from the eight monitored wooden elements of the cabin were applied to the decay model developed by Brischke and Meyer-Veltrup (2016). The annual dose d_a was calculated on the basis of the data from one full year of daily measurements, as can be seen from Table 4. The dose was almost insignificant on the first floor (F5 and F6), and very low on the façade, i.e. 2.1 and 2.4 days, respectively, with optimum conditions for fungal decay through an entire year. The estimated service lives for all these elements were consequently extremely high, according to the model even infinite, indicating an extremely low risk of decay. As expected from the prediction, no signs of decay were observed, either in the first floor nor on the façade.

In contrast, decay, partly severe decay, was found on various pillars in the bunker. Coinciding with these findings, the moisture and temperature-induced daily dosage d_a was the highest with element F1, which already showed severe decay and fruiting bodies of decay fungi after 4 years, followed by two further pillars (F2 and F4), which both showed significant decay after 4 and 6–7 years, respectively. Based on the model for brown rot decay (i.e. onset of decay after 356 days of optimal conditions) the ESL_B was 2.3 years for F1, 2.6 years for F4 and 6.3 for F2, which fits exactly with the observations made in the cabin. For pillar F3, where no signs of decay had yet been found, a service life between 11.4 and 21.4 years was predicted, depending on the rot type.

The decay model led to correct service life predictions in eight cases, but among other boundary conditions, the material resistance was assumed to be equal to that of untreated Norway spruce. In contrast, the studied cabin was built from Cu-EA-treated spruce wood. Again, in agreement with the results from the retention analysis, the treatment needs to be considered to have been fairly poor, not providing any significant protection. This presumption is supported by field testing of poorly copper-treated wood (Humar *et al.*, 2016). It was not therefore surprising that the modelling assumptions made from untreated wood could be transferred to Cu-EA-treated spruce free of constraints.

Table 4. Mean annual dose D_a and estimated service life for white/soft (ESL_{WS}) rot and brown rot decay (ESL_B) (material-climate-related measures are based on a period of one year (01.04.16–31.03.17).

No.	D_a	ESL_B	ESL_{WS}	State of element after visual inspection and resistograph measurements
F1	156.9	2.3	4.3	Severe decay and fruiting bodies after 4 years or less
F2	56.6	6.3	11.8	Decay after 6–7 years
F3	31.3	11.4	21.4	No decay
F4	136.5	2.6	4.9	Decay after 4 years or less
F5	0.0	∞	∞	No decay
F6	0.0	∞	∞	No decay
F7	2.1	171.3	322.4	No decay
F8	2.4	149.5	281.4	No decay

4. Conclusions

Moisture monitoring is a very useful method for evaluating micro-climatic conditions in buildings. Significant variations among micro-climates had strong effects on the material climate and, consequently, the expected service life of different structural elements of the studied historic site. For restoration purposes and maintenance of cultural heritage objects in particular, reliable tools are needed to evaluate the effectiveness of both design measures and material protection. In the case of the bunker structure in the WWII partisan hospital Franja, it became evident that (1) superficial preservative treatment of the wood was far from sufficient and (2) the decay risk varied drastically, depending on the micro-climate. In addition, the very particular situation of the cabins in a gorge with a permanently running stream, high RH all over the year and very limited amount of direct solar irradiation, became evident over the course of the monitoring.

Moisture monitoring of valuable buildings and monuments might also serve as an early warning system but, as shown in the case of Franja hospital, the reliability of a monitoring concept strongly depends on the number of sensors. The positioning of sensors and interpretation of the collected data require detailed knowledge of timber engineering and wood pathology.

This approach can be applied on novel wooden constructions as well, and is becoming more and more important on multi-storey buildings to control leakage and mis-use of the building.

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ORCID

Miha Humar http://orcid.org/0000-0001-9963-5011

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