AKADÉMIAI KIADÓ

Moisture content changing of a historic roof structure in terms of climate effects

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ABSTRACT

Timber is a widely used material in construction. The moisture content has a significant impact on the mechanical and physical properties of it. This paper studies how the moisture content values are directly connected to the climate conditions, especially temperature and relative humidity, by measuring these factors for a non-renovated historical timber roof for a one-year period, combined with meteorological data for Pécs since 1901. The fluctuation in moisture content values created instability in the water content of the structural elements due to absorption and release of water in order to reach the equivalent moisture content point. This process led to continuous volume increase-decrease of the timber, thus to formation of cracks, discoloration and harmful fungi development.

KEYWORDS

climate change, temperature, relative humidity, moisture content, timber, historical buildings

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1. INTRODUCTION

Timber is one of the oldest materials that humanity uses in buildings and engineering structures. Due to its advantageous physical and mechanical properties, - lightweight, durability, high strength to weight ratio - it is used for various construction purposes. Wood is a renewable material thus its use can reduce the energy consumption and carbon-dioxide emission [1]. In seismic zones, the flexibility of wood combined with its light weight, makes wood a suitable alternative to steel and concrete [2]. In the last decade, usage of wood in construction has been continuously increasing especially in Europe [3]. In Hungary the annual consumption of wood per capita is 0.70 m^3 [4].

Besides the many advantages of the timber, there are some disadvantages, what need to be considered. Buildings and wood structures need to be frequently renovated; the old used materials need to be replaced, increase of lifetime and permanent maintenance works to resist climate conditions need to be performed [5]. Wooden structures need also to be continuously evaluated, since cracks, splits and fungal decay can be formed due to aging and climate factors [6, 7].

In order to understand the climate interaction with the wooden elements, besides the general understanding of the climate factor effects on timber, a local climate study is also necessary. According to the classification made by the Hungarian climatologist György Péczely [8], the climate of Pécs has been described six decades ago as moderately warm and moderately dry with annual mean temperatures between 10 and 11 °C. July was the warmest month, with temperature ranging between 27 and 30 °C, however in the last years, temperatures over 35 °C have also been experienced.

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The annual precipitation amount is about 650–700 mm, and the chance of rain is high in May, June, and July. Pécs is classified as a moderate windy region [9]. The climate impact on the wooden texture has been supported by various research results; a study from the 1870s until today made clear that the wood annual growing is gradually becoming lighter by up to 12%. The tree growth has also accelerated in Central Europe, the newly produced wood contains less material, thus it becomes weaker [10].

The climate impact on the wooden elements can be seen in form of shrinkage, swelling, and deformation, which leads to the decrease of the stiffness and strength, which appear as cracks along the elements. There may also be a risk of fungal decay in wood elements at temperatures above 23 °C and Relative Humidity (RH) above 42%. That explains the importance of taking the Moisture Content (MC) in consideration when wooden structures are studied. Ultraviolet radiation has also harmful impact on the wood because it supports the drying process and changes or destroys the lignin [11–13].

This paper aims to measure the impact of several climate factors as Temperature (T) and (RH) on a cultural heritage wooden building in Pécs during four seasons, in parallel with MC measurements of the wooden elements. The measurements are combined with a climate factor study over the past 120 years, thus a relation between climate factors and the observed damages can be set.

2. METHODOLOGY

The Civil Community House dates back to the 19th century. It is located in Pécs at Szent István square. From its construction in the early 19th century until now, the house has passed through four renovations stages. These renovations were made on the whole structure except the roof level [14]. The roof level nowadays is used as a storage area.

In order to evaluate the climate impact on the wooden roof, the climatic history of the region needs to be understood. The meteorological data over 120 years used in this study were collected by the "Hungarian Meteorological Service (OMSZ)" [15]. The study focused on the yearly values of maximum and minimum temperatures, the number of summer and winter days. The aim of the meteorological data analysis was to draw conclusions on the change of the climate factors in time and relate these changes to the damages that the Civil Community House needs to bear.

The on-site measurements were composed of visual inspection and T, RH and MC measurements. A Kimo AQ200 device has been used to measure indoor and outdoor T and RH, while the MC measurements were done by using a Testo 606-1 device. Daily/weekly visits have been arranged to the roof, however visiting hours were limited because of COVID 19. The outdoor measurements were done in the shadow to avoid the direct effect of sunlight. MC measurements were done on different structural elements (columns, beams, and rafters), these measurements were done only on the surface of the wood, because destructive measurements were not allowed.

Scanning Electron Microscope (SEM) measurements were done by using a TESCAN VEGA 3S type instrument. The measurements have been done by fixing the electron beam at 5 kV and by taking several images from 50 × to 900 × magnifications [16]. Small pieces (of several mm) were collected from different structural elements to visualize the effects of the MC on the wood cell walls and relate them to the level of damage of the roof elements. Samples were selected according to the following criteria: structural variety (columns, beams, etc.,), lightened by sun or not, damaged and undamaged. Samples have been measured at different moisture content levels from 0% to 24%.

3. RESULTS AND DISCUSSIONS

3.1. Analysis of meteorological data

Figure 1 shows that the number of summer days/year and heat days/year - over the last 120 years - were fluctuating. The number of summer days versus year graph shows a wavy pattern, with periods of 50–60 years. A summer day is defined as a day with a temperature higher than 25 °C, and a heat day is defined as a day with a temperature above 30 °C. The last increasing period ended in 2013, thus in the next 30 years a minimum for the summer and heat days/year can be predicted, however it does not mean that the same

a)
b)

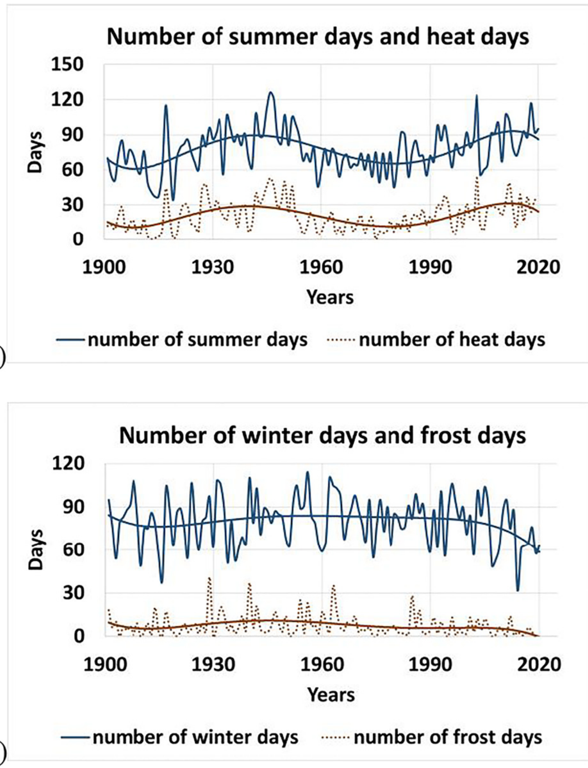


Fig. 1. Meteorological study of Pécs over 120 years: a) number of summer days and heat days; b) number of winter days and frost days

minimum value will be achieved as 40 years ago. The number of winter days versus year graph shows a massive drop started in 2002 that shows the decrease of the number of cold winter days with at least 5 days compared to the minimum of year 1916. A winter day is defined as the day with a minimum temperature below 0 °C, and a frost day is defined as a day with a temperature below 10 °C. Studying the graphs it could be concluded that shorter winter periods can be expected for the next 10–20 years, which can be regarded as an effect of the global warming, however the forthcoming "summer day's valley" can moderate this effect. The maximum and minimum temperature values do not show a clear increasing or decreasing tendency.

The analysis of the meteorological data shows that a massive fluctuation of the various climate factors during the past 120 years had to be experienced by the Civil Community House. These fluctuations lead to deterioration of the wood driven by processes like volume changing, MC changing, exposure to UltraViolet (UV) radiation, and wetting by rainwater. Being both hygroscopic and orthotropic material, wood is subject to swelling and shrinkage cycles that lead to formation of cracks and high deformation of timber elements, which reduce the mechanical and functional performance, providing favorable environment for biological deterioration in form of fungi and insects.

3.2. Visual inspection results

The visual inspection of the wooden roof shows that the roof was built as queen post truss system, in order to reduce the cost and to cover the large area of the floor, which is around 190 m^2. The roof is supported by one brick wall in the middle; the plan view of the roof has U shape with two different sections along it as it is shown in Fig. 2. A proper ventilation system is missing. Most of the used wood is pine (pinus silvestris). Figure 2 shows the cracks and splits positions found in the roof on the two sectional views: A-view is a general one and B-view shows the middle supported by brick wall. Table 1 shows the results of the visual inspection. The two main reasons of the damages are the MC change and the wood ageing that can be referred to the climate change cycles and the lack of surface treatment and rehabilitation. Struts and posts are highly damaged, and the color of the elements tends to be whiter when the elements have higher elevations. The timber elements were not covered by any protective layer, and the top covering layers of the roof have passed their service life (40–50 years in average). Thus, almost all the elements are deteriorated. It can be estimated that 30–40% of the roof elements are severely deteriorated.

However, the investigated period is very short, the visual inspection and the analysis of the meteorological data reflects the history of the whole structure. The lack of any

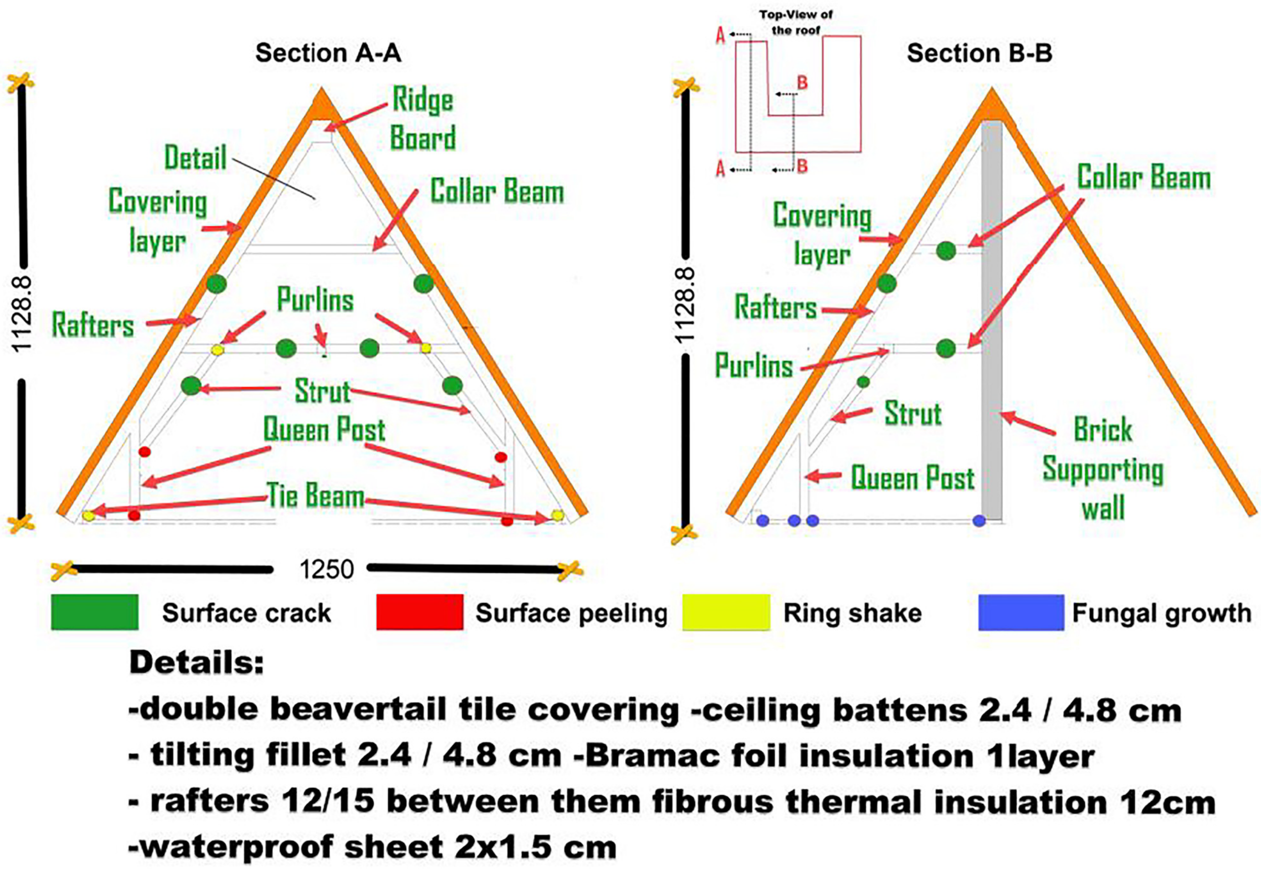


Fig. 2. Sectional view of the roof

Table 1. Visual inspection results

Defect type	Description	Formation reason	Affected elements
Ring shakes	Longitudinal separation of wood fibers in the tangential direction	Wood ageing, site conditions	Mainly tie beams and some purlins
Surface peeling	Loss of the wood fibers along the element, at few mm from the surface	Constant change of MC and site conditions	Posts and struts
Surface whitening	Tendency of the surface color to white	High MC	Posts and struts
Surface cracks	Mass loss of the wooden material, 3–4 cm peeling along the element	Wood ageing and load bearing combined with MC change. Swelling and shrinkage	Struts ends and Posts ends.
Fungal Growth	Fungi growth on the wooden surface	Climate conditions and high MC	Tie beams and posts
Longitudinal cracks	Cracks spread along the element ranging between 2 and 30 cm (could be more in some elements)	Structural loads and site conditions	All structural element types
Discoloring	Elements lose their original color to become more faded	High M.C	All structural element types

reconstruction of the roof level and the absence of the proper insulation layer led to these expected failures. The meteorological data studied for the Pécs region shows that during the past decades the temperature and relative humidity fluctuations affected the moisture content of the timber in a similar way to the studied period.

3.3. On-site measurements results

The measurements have been done along four seasons on different damaged and undamaged structural elements. MC values were calculated as the average of the MC values along the element (3-5 spots along the element have been measured with three measurements in the same spot). The summer measurements results are shown in Fig. 3. In the summer period the outdoor temperature ranged between 18 and 30 °C, while the indoor temperature values were always less than the outdoor values by only 1–2 °C. Outdoor RH values ranged between 35 and 80%, and the indoor values were always higher by 7–11%. The summer period T and RH values (especially between 20th of July until 18th of August) show fluctuations, however these fluctuations are followed in a much slower way by the changes of the MC values. It can be observed that the average MC values follow the T and RH very slowly (see Fig. 3c). The elements MC values range between 10 and 14%.

The autumn period temperatures, ranging between 2 and 15 °C show a difference of 1–2 °C between indoor and outdoor values, while RH values increase up to 60–95% with a difference of 10–14% between indoor and outdoor values. Beams MC values ranged between 13 and 18%, rafters and columns values ranged between 16 and 24%. Autumn measurements showed similar tendencies to summer, the MC changes did not follow the daily RH values, however the average values shown similar increasing and decreasing tendencies as the average of the indoor and outdoor RH.

In the winter and spring seasons, both T and RH were fluctuating along the season, and contrary to summer and autumn, the MC values followed these fluctuations for all the elements. T range was −4–14 °C and 2–33 °C for winter and spring respectively. RH range was 50–98% and 30–95% for

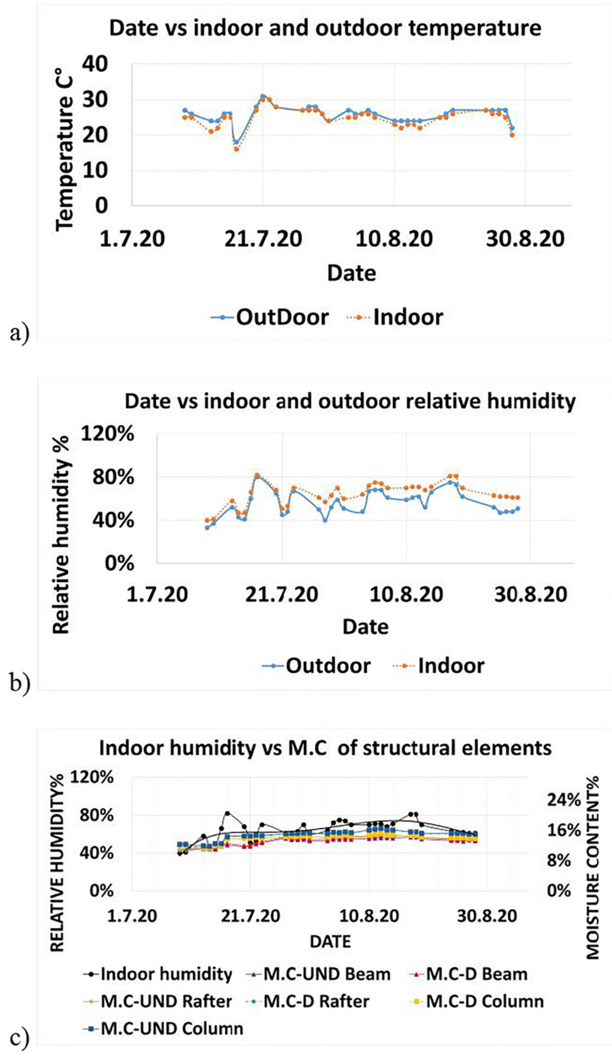


Fig. 3. On-site summer measurements: a) date vs. indoor and outdoor temperature; b) date vs. indoor and outdoor RH; c) indoor humidity vs. MC of structural elements

winter and spring respectively. The range got wider in both seasons, which explains the fluctuation in MC values. In spring the elements MC values ranged between 9 and 22%, while in winter beam MC ranged between 11 and 18%, columns and rafters values ranged between 13 and 25%.

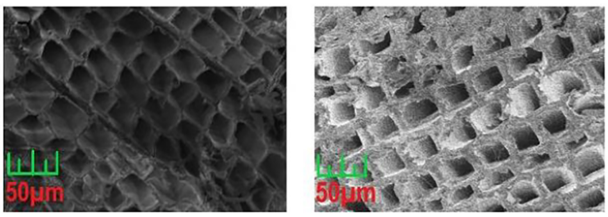
The measurements showed that the main damages in the wooden elements in the roof happen during the spring and winter seasons because there is a high fluctuation in RH and T values, resulting in absorption and release of the water to adapt to reach the Equivalent Moisture Content (EMC) point. This way the wooden cell size changes (shrink and swell), generating internal stresses that will develop new cracks and splits.

3.4. Scanning electron microscope measurements results

The measurements were done on different samples: girders, columns, inclined and horizontal bracing, damaged and un-damaged, lightened or not by sun. The aim of the measurements was to visualize the effect of the MC on the wooden cells by measuring the size of the cells at different MC values. The classification values of the MC were defined according to Eurocode 5 [17]. Three classes have been defined: class 1, where MC is between 0 and 12%; class 2, where MC is between 12 and 20% and class 3, where MC is higher than 20%, at a temperature of 20 °C (room temperature).

Figure 4 shows the SEM images of a wooden sample taken from a damaged girder, lightened by the sun. Figure 4a shows the sample with zero MC and a horizontal wall thickness of an average of 4.3 μm, and Fig. 4b shows the sample with a MC of 12.7% with a horizontal wall thickness of an average of 7.7 μm. The increase in the MC is translated directly into an increase in the walls thickness. It has been noticed that damaged elements were more affected by increasing the MC.

The capacity of the wood to absorb water depends on the type of the wood and the structural condition of the sample, where damaged and cracked elements can absorb more water. The samples have been studied by SEM: S1 – girder, damaged, sun lightened, S9 – column, un-damaged, not sun lightened and S11 – horizontal bracing, un-damaged, not lightened by the sun. S1 had a wall thickness that kept increasing with the MC, but S9 and S11 showed that the cells reached their limit of water absorption capacity and the value of the wall thickness was approximately the same for the 2nd and the 3rd MC classes. When the volume of the wooden cells increases, new cracks develop, and the continuously absorbed water creates a humid environment for fungi growth. Both effects will have high negative impact on the mechanical, physical, and thermal properties of the wood.



a) b)

Fig. 4. Wood sample 1 analyzed with SEM, a) MC = 0%; b) MC = 12.7%

3.5. Data evaluation

In order to evaluate the measurement results statistical calculations have been made for all the seasons. Table 2 shows the calculated statistical values for the summer season, Table 3 shows the correlation between the MC and the climate factors.

The data approved the stability of MC values for the structural elements in both summer and autumn seasons. Despite the high dispersion in T values in autumn, the MC values have small variance (σ^2) and standard deviation (σ) because of the uniformity in RH values. The summer is considered as the most stable season because of the smallest σ^2, and σ values. The highest dispersion in the T and RH data were in spring and winter, with highest values of σ^2, and σ that translated to high dispersion in MC values in the structural elements. Thus, the most severe impact on the roof happened during spring and winter.

The data show that the impact of RH on the MC values is greater than the impact of the T on them. Higher dispersion in RH means high σ^2 and σ values and lower stability in MC values. In order to translate this result into a numerical one,

Table 3. Correlation factor between MC and climate components

Correlation between MC		
	$RH_{-Indoor}$	$T_{-Indoor}$
Undamaged Beams	0.90	−0.60
Damaged Beams	0.89	−0.65
Undamaged Rafters	0.89	−0.71
Damaged Rafters	0.87	−0.76
Undamaged Columns	0.87	−0.80
Damaged Columns	0.87	−0.79

Table 2. Statistical evaluation of the measured data for the summer season

	T_{out} °C	T_{in} °C	RH_{out} %	RH_{in} %	MC% Undamaged beam	MC% Damaged Beam	MC% Undamaged Rafter	MC% Damaged Rafter	MC% Undamaged Column	MC% Damaged Column
Summer-Season										
Avg-Value	25.91	24.85	55.62	64.15	12.95	13.37	13.71	14.64	13.88	14.77
σ^2	5.42	7.46	1.28	1.11	0.01	0.01	0.01	0.02	0.01	0.02
σ	2.33	2.73	11.33	10.53	1.09	1.13	1.20	1.35	1.06	1.30

the correlation factor between the climate components and MC for the whole measuring period has been calculated and is shown in Table 3. The table shows how the RH has more impact on MC values than the T does. Damaged elements are more affected than the undamaged ones, and as the bearing load increases on the element, the impact gets higher. For example, in this roof system, the columns are the main structural elements to resist the loads and they are the most affected elements.

4. CONCLUSION

Preservation of historical and heritage structures is of high importance, the used techniques depend on the originally used materials and on the suffered damage of the elements. The timber roof of the civil community house needs an urgent rehabilitation. According to the meteorological data collected, the roof passed through frequent climate factor fluctuation periods, combined with the absence of the structural reinforcement, which led to mechanical and physical weakening of the these elements, as expected. Most of the timber elements were damaged. The damage ranges from moderate to severe cracks along the members, as well as color change in more than 70% of them. The visual inspection and the seasonal on-site measurements confirmed what the meteorological data had predicted.

The damage that the roof is facing is caused by both climate conditions, and the bearing load on the structural elements. These damages decreased the quality of the energy transfer system in the roof, which translated to higher exposure to T and RH, showed also by the 98% correlation factor between the indoor and the outdoor T and RH values for the whole period. This leads to higher MC fluctuation, which increased the risk of damage. As it was mentioned, the roof needs an urgent rehabilitation, and finding an appropriate solution for the sealing of the roof against humidity.

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