Breuer Marcell Doctoral School

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Pécsi Tudományegyetem
Műszaki és Informatikai Kar

Breuer Marcell
Doktori Iskola

Climate Change Impacts on Heritage Timber Structures

Thesis Booklet

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1. Introduction

1.1. Background

This is the corrected part, you can decide if you use it or you let the previous version: Climate change impacts are increasingly being felt worldwide. Over the last thirty to forty years, climate change has emerged as a significant problem, with severe social and economic consequences. Various research groups are committed to identifying the causes and mitigating the effects of the high-impact weather events. The present research joins this challenge and aims to conduct a study in the field of preserving timber heritage structures from the impacts of climate change.

Climate change has profound effects on heritage wooden structures, posing new challenges to their preservation and management. These impacts are expected to intensify in the coming decades. The changing climate exposes cultural heritage to diverse pressures and risks not previously experienced. The consequences of climate change on wooden structures can result in deterioration, damage, and degradation. The vulnerability of heritage wooden structures to climate change is influenced by various factors, including temperature, humidity, precipitation, and extreme weather events.

This research addresses the urgent issue of climate change, with a specific focus on its implications for Hungary. It provides a comprehensive analysis of how these changes impact both indoor and outdoor wooden structures. By investigating the complex interplay between environmental factors and wood characteristics, this study offers insights into the intricate relationship between climate shifts and material behavior. This contributes to a deeper understanding of the broader implications of climate change on our built environment. The research conducts an in-depth examination of its multifaceted impact on two distinct wooden structures: an indoor construction and an outdoor installation. Furthermore, it examines the alterations observed in the softwood properties when exposed to varying humidity levels within controlled laboratory settings.

1.2. Research questions

During the theoretical study and the research work, the need to answer several specific research questions related to the climate and climate change appeared:

- What are the microclimate peculiarities of Hungary compared to Central-Europe, and how the climate change affects the characteristics of this microclimate?
- How to relate the climatic history of the region to how wood elements interact with climate changes?
- What are the most important climate factors affecting the deterioration of wooden elements?

- What techniques and methods monitor and calculate the value of current climate variables, and how to assess the current state of the structure?
- How does climate change affect the physical and mechanical properties of wood elements?
- How does climate change affect the fracture behaviour of the wooden elements?
- How the continuous monitoring and periodic maintenance, can have a positive impact on the structure?

1.3. Principal objectives and scope

The main objectives of the present research were:

- Investigate the relationship between climate components (e.g., temperature, humidity, precipitation) and their impact on heritage timber structures;
- Analyse historical meteorological data for identifying climate change trends and their potential influence on timber element behaviour and structural integrity;
- Study the reaction of heritage timber structures to various climate components and assess their vulnerability to climate-induced stressors;
- Examine the physical and mechanical properties of wood through laboratory testing under

controlled climate conditions, simulating projected climate change scenarios;

- Assess the long-term implications of climate change on the durability, stability, and preservation needs of heritage timber structures.

Thus, the methodology can be summarized in the following points:

Meteorological data analysis:

- Collect and analyse historical meteorological data from different geographical regions;
- Identify the key climate components relevant to the study;
- Compare and evaluate the climate trends over a specific period to discern patterns and variations.

Effect of climate components on timber elements:

- Conduct field investigations of selected heritage timber structures to evaluate their current condition and exposure to climate elements;
- Monitor and measure the reactions of timber elements to varying climatic conditions;
- Identify the factors contributing to timber degradation and damage in different climates.

Laboratory testing:

- Selection of representative wood species commonly used in heritage timber structures;
- Conduct controlled laboratory tests to assess the impact of climate-induced stressors on wood

properties (e.g., moisture content (MC), cracks and failures, mechanical strength);

- Analyse the results to determine how wood properties change under different climate scenarios.

Preservation and adaptation strategies:

- Assess existing preservation techniques and study their effectiveness in mitigating climate change impacts on heritage timber structures;
- Develop recommendations for adaptive preservation strategies based on the research findings.

Limitations:

- The study focuses on heritage timber structures in specific geographical regions and may not cover all possible variations in climate conditions;
- In the absence of a climate chamber, standardized laboratory conditions could not be produced directly, however the results were translated to standard conditions. Therefore, the conclusions are not generalized, but valid for the used conditions, described in the Chapters of the Thesis.

2. Scientific thesis

Thesis 1. Regional climate change effects on timber structures (related publications 1, 2, 5, 6, 7, 8, and 9)

Based on visual inspection results, on-site weather parameter measurements, timber moisture content measurements during four seasons, and statistical analysis of the collected data, I have demonstrated that the fluctuations in temperature and relative humidity values, both, indoors (in the Pécs region) and outdoors (in the Buda-Hills region), exert a greater impact on timber building elements than the average annual and/or seasonal temperature increase. Despite the largest seasonal increase in the maximum temperatures occurring in summer (2.1 °C from 1981 to 2020) and a decrease in precipitation quantity, attributed to global warming effects.

1a. I have demonstrated that fluctuations in outdoor temperature and relative humidity have the most significant impact on untreated indoor timber structures during the spring season. The average amplitude of outdoor temperature, outdoor relative humidity, and moisture content for beams, rafters, and columns measured during spring exceeded the values recorded during the rest of the year, with rates ranging between 28 and 79 %. Similarly, the calculated standard deviations for the measured temperature, relative humidity, and moisture content during spring surpassed the values of other seasons by 13 to 74 %, indicating that the variation in climate factors and moisture content of the wood during the spring season was the highest.

1b. I have demonstrated that fluctuations in indoor temperature and relative humidity have the most significant impact on surface-treated outdoor timber structures during the spring season. The average amplitude of outdoor temperature, outdoor relative humidity, and moisture content for columns, stairs, and fences measured during spring exceeded the values recorded during the rest of the year, with rates ranging between 19 and 66 %. Similarly, the calculated standard deviations for the measured temperature, relative humidity, and moisture content during spring surpassed the values of other seasons by 34 to 75 %, indicating that the variation in climate factors and moisture content of the wood during the spring season was the highest.

Therefore, by considering only the average global or regional temperature and yearly precipitation values, the precise prediction or modelling of the future behaviour of new and cultural heritage timber structures becomes challenging. I recommend that, for future structural integrity calculations, behaviour modelling, or lifetime prediction of timber structures, in addition to changes in yearly and seasonal average temperature and relative humidity values, the seasonal effects of the temperature and relative humidity fluctuations, as well as the frequency and the amplitude of fluctuations – preferably based on on-site measurements – should also be taken into account.

Thesis 2. Interdependence between climate factors, surface treatment and aging of timber elements (related publications 1, 2, 5, 6, 7, 8, and 9)

Using on-site moisture content measurements indoors and outdoors, along with semi-destructive scanning electron microscopy measurements, I demonstrated the circular dependency among moisture content, the re-acclimation process of the wood, and the aging of timber elements.

2a. Using scanning electron microscopy measurements, I assessed the cell wall thickness in dry and saturated wooden samples obtained from untreated indoor timber elements (Pécs site). I demonstrated that damaged wooden elements exhibit a higher susceptibility to an increase in moisture content. The average increase in wall thickness for the damaged elements was 3.5 µm, whereas for the undamaged elements, it was 2 µm. The dynamic water absorption and release processes, particularly pronounced in more damaged elements, triggered a re-acclimation process in the wood to achieve equilibrium moisture content. Due to the lack of renovation and surface protection for the examined roof structure of the Civil Communities House (Pécs), this re-acclimation occurred extensively over many decades. In recent decades, the processes intensified further due to global warming. Consequently, damaged elements absorbed more water, initiating a re-acclimation process that led to additional damage, creating a self-perpetuating circular cycle. This pattern was evident in the moisture content values of damaged elements throughout the seasonal study, consistently remaining 1-3 % higher than those of undamaged elements. Therefore, I concluded that the moisture fluctuations in untreated timber elements give rise to a self-sustaining circular damage process, wherein greater wood damage leads to more significant moisture content fluctuations, resulting in further damage.

2b. Based on the calculated correlation coefficients between timber moisture content and climate factors for surface-treated outdoor timber elements at the Buda-Hills site, I have demonstrated that load-bearing functional elements are more susceptible to variations in climate factors than non-structural elements. Specifically, the correlation coefficients between moisture content and temperature, and moisture content and relative humidity for the load-bearing elements were -0.54 and 0.40, respectively. In contrast, for non-load-bearing elements, the correlation coefficients ranged between -0.10 and -0.25 for moisture content–temperature correlation, and between -0.18 and -0.38 for moisture content–relative humidity correlation.

In the absence of periodic rehabilitation for the studied timber structure at the Pécs site, the correlation coefficient increased to -0.71 for temperature–moisture content and to 0.87 for relative humidity–moisture content. Therefore, I have concluded that, especially in the case of cultural heritage building timber elements, preserving the structural integrity of wooden elements requires tailored surface treatment methods. These methods should be designed to suit both the location and the building, taking into consideration climatic conditions, and preserving the character of the structure.

Table 1. 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

Table 2. Correlation factor between MC and climate components

Correlation between MC		
	T	RH
Columns	-0.54	0.40
Stairs	-0.25	-0.36
Fences	-0.11	-0.18

Thesis 3. Relationship between the fracture behaviour of the softwood and moisture content (related publications 1, 3, 4, and 6)

Using the four-point bending test method on three sets of softwood (Picea Abies) samples, I have demonstrated, that as moisture content increases, the fracture behaviour of timber elements shifts from brittle to ductile or semi-ductile behaviour. This transition enhances the possibility of achieving high displacements, but comes at the cost of weaker resistance and strength against static and dynamic loads. Among the low moisture content test samples, tha majority (56.5%) exhibited cross-grained tension failure, which transitioned to buckling failure (83% of failures) with increased moisture content, expected under bending load effects.

I concluded that structural timber elements, in the absence of protection, are highly affected by fluctuating weather factors, especially the relative humidity and temperature. The increased moisture content of timber elements is expected to decrease the load-bearing capacity of the structural support system. Conversely, the surface-treated set of samples showed reduced susceptibility to the moisture, with the fracture behaviour of the majority of the samples (63.5%) being brittle, exhibiting cross-grained tension failure. Based on the four-point bending mechanical tests, I have demonstrated that even a commercially available outdoor silk-gloss thick glaze protecting layer significantly mitigates the effect of the moisture change by improving its mechanical resistance.

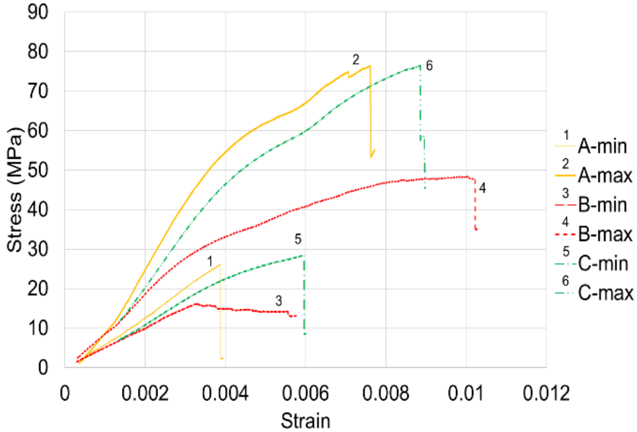

Figure 1. Stress vs. strain diagram for maximum and minimum strength of rupture of tested groups

Thesis 4 Relationship between the moisture content and mechanical properties of softwood (related publications 1, 3, 4, and 6)

I have demonstrated that under extreme conditions involving full water saturation of wood, the mechanical properties of softwood timber elements can still be maintained within the minimum allowable strength grade. Conducting a four-point bending mechanical test on a statistically significant sample number, I have proven that the full water saturation (18.2 % average moisture content increase) of the wood material decreases both the modulus of elasticity and modulus of rupture by 35%, thereby changing the timber grade to the prohibited category for construction.

In contrast, I have also proven that the commercially available outdoor silk-gloss thick glaze surface treatment, combined with full water saturation (10.4 % average moisture content increase) of the wood, maintains the modulus of rupture decrease at 11 %, and the modulus of elasticity decreases at 15 % compared to values measured for dry sample conditions. Consequently, I concluded that even under extreme weathering conditions, such as severe and frequent heavy rainfall, flash floods, and extremely humid environments, the mechanical properties of surface-treated softwood elements with load-bearing functions can be maintained in the safe category.

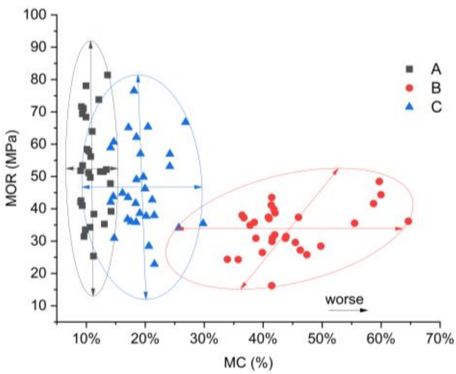

Figure 2. MOR vs. MC 95% confidence ellipse graphs for the three groups of tested samples

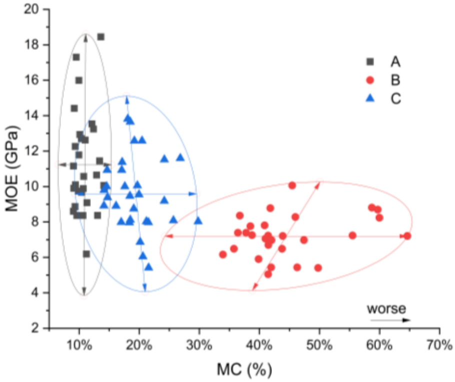

Figure 3. MOE vs. MC 95% confidence ellipse graphs for the three groups of tested samples

3. Publication list

1- Kherais, M., Csébfalvi, A., & Len, A. (2020). The climate impact on timber structures. Int. J. Optim. Civil Eng, 11(1), 143-154.

Status: Published

2- Kherais, M., Csébfalvi, A., & Len, A. (2022b). Moisture content changing of a historic roof structure in terms of climate effects, Pollack Periodica, 17(3), 141-146. doi: https://doi.org/10.1556/606.2022.00546

Status: Published

3- Kherais, M., Csébfalvi, A., & Len, A., Fülöp, A., Pál-Schreiner, J. (2023). The effect of moisture content on the mechanical properties of wood structure, Pollack Periodica. doi: 10.1556/606.2023.00917

Status: In press

4- Kherais, M., Csébfalvi, A., Len, A., & Fülöp, A. (2022a). How to protect wooden structures from damages caused by weather changes - study case. 25th Spring Wind Conference, 339-350.

Status: Published

5- Kherais, M., Csébfalvi, A., & Len, A. (2022c). Moisture Content Impact on Wooden Structures. 10th Jubilee Interdisciplinary Doctoral Conference 2021, 395-407.

Status: Published

6- Kherais, M., Csébfalvi, A., & Len, A. (2022d). Climate impact on timber structures. Abstract book for the18th miklós iványi international phd & dla symposium. Pécs, Hungary. Pollack Press p. 62

Status: Published

7- Kherais, M., Csébfalvi, A., & Len, A. (2021a). Evaluation of measurements on roof structure of a historic building and comparison of the results as a function of environmental changes. Abstract book for the 17th miklós iványi international phd & dla symposium. Pécs, Hungary. Pollack Press p.68.

Status: Published

8- Kherais, M., Csébfalvi, A., & Len, A. (2021a). Effect of the moisture content on wooden structures. Abstract book for the XIX. jános szentágothai multidisciplinary conference and student competition. Pécs, Hungary. Szentágothai János Szakkollégium p. 55-56.

Status: Published

9- Kherais, M., Csébfalvi, A., & Len, A. (2020). Expected impact of climate change on the physical properties and load-bearing capacity of timber structures. Abstract book for the 16th miklós iványi international phd & dla symposium. Pécs, Hungary. Pollack Press p.72.

Status: Published

4. Conference lectures

Conference name	Lecture title	Date	Location
16th Miklós Iványi International PHD & DLA Symposium	Expected impact of climate change on the physical properties and load-bearing capacity of timber structures	27/10/2020	Online
XIX. Szentágothai János Multidiszciplináris Konferencia	Effect of Moisture Content on Wooden Structures	26/03/2021	Pécs - Hungary
17th Miklós Iványi International PHD & DLA Symposium	Evaluation of measurements on roof structure of a historic building and comparison of the results as a function of environmental changes	26/10/2021	Pécs - Hungary
10th Jubilee Interdisciplinary Doctoral Conference	Moisture Content Impact on Wooden Structures	13/11/2021	Pécs - Hungary
XXV. Tavaszi Szél Konferencia 2022	How to protect wooden structures from damage caused by	07/05/2022	Pécs - Hungary

	weather changes (Study Case)		
MIK PARTNERS Szakmai Nap 2022 és Baranya Megyei Mérnöki Kamara 25. Jubileumi Mérnöknap	Climate impact on timber structures	20/10/2022	Pécs - Hungary
11th Jubilee Interdisciplinary Doctoral Conference	Change of mechanical properties of timber structures caused by the moisture content variations	26/11/2022	Online