AKADÉMIAI KIADÓ

The effect of moisture content on the mechanical properties of wood structure

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Pollack Periodica • An International Journal for Engineering and Information Sciences

19 (2024) 1, 41–46

DOI: 10.1556/606.2023.00917

Received: July 12, 2023 • Revised manuscript received: October 1, 2023 • Accepted: October 16, 2023
Published online: February 7, 2024

ORIGINAL RESEARCH PAPER

ABSTRACT

In the last two decades, the utilization of timber in construction has gained increasing attention among researchers and sustainable building designers. Therefore, studies of climate impact on timber structures have been conducted, many of them focusing on the moisture content caused changes in timber. In the present study, four-point bending tests have been performed on three testing groups, containing 30 samples each. The first group has been tested under its natural conditions, while the second and the third groups were fully saturated with water. The third group was glazed with a protection material. The results show the changes in the modulus of elasticity and the modulus of rupture caused by the moisture content increase. In the same time the material behavior changed from brittle to semi-ductile or ductile for some samples.

KEYWORDS

moisture content, timber, modulus of elasticity, modulus of rupture, four-point bending test, Poisson distribution, stress, strain

1. INTRODUCTION

Wooden structure architecture in European countries has special style and artistic characteristics with a history of several hundreds of years, having important cultural heritage value. The most important aging processes for timber members are the biological damages and natural aging. The biological damage is caused by microorganisms (fungi, termites, etc.,), resulting in serious problems, like wood decay, defects, or cavities [1–3]. Natural aging effects are caused mainly by UltraVioley (UV) light, temperature and air humidity variations, precipitation, and wind. The aging effects change the wood cell size, resulting in changes of the microstructure, macroscopic physical characteristics, and mechanical properties [4–7]. The dimensional stability and the appearance – color and shape – of the timber members can be evaluated through the hygroscopic behavior parameters, like Equilibrium Moisture Content (*EMC*). The main mechanical property parameters that characterize the timber members under bending load are the Modulus Of Rupture (*MOR*) and Modulus Of Elasticity (*MOE*) [8–10].

These parameters can be measured using destructive or non-destructive testing. Non-destructive testing methods in the case of the timber are based mainly on the propagation speed of the ultrasonic waves, or acoustic spectral analysis [3]. The destructive testing is based on the incremental displacement system or force system until the tested samples fail. In most cases three-point or four-point bending tests are performed to obtain the flexural properties of the materials [8, 11].

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Since wood interacts directly with various environmental factors, the protection of wood from these factors that pose a threat to its physical and mechanical properties, is indispensable. Various coatings can be used to protect timber elements.

The covering usually lasts for 2–3 years [12] then new treatments must be implemented. Besides their artistic function, paints provide protection against weathering. A nonporous, hydrophobic paint coating inhibits moisture penetration and thus paint discoloration caused by wood extractives, inhibits paint peeling, and warping of the wood. The use of appropriate pigments will almost eliminate photo-degradation of the wood surface. However, paints and protective layers are not total preservatives; they cannot prevent decay if the environment is conducive to fungal growth, the wooden structure is directly exposed to sun and rain effects [11]. Besides the severity of the climate conditions, the serviceability of the paint on timber structures is affected by three significant factors: the wood type and quality, the design and use of the building, paint type and quality [12, 13].

Previous papers [4, 5, 14] discussed the climate impact on heritage timber structures, focusing on the relationship between Moisture Content (*MC*) change and the climate components effects, like temperature (*T*) and relative humidity (*RH*). The present paper aims to study the changes in the mechanical properties of the timber, especially the *MOR*, which is defined as a specimen's maximum strength just before failure, and the *MOE*, which is defined as the ratio between the active stress load and the resulting strain (deformation) that the wood exhibits along its length, by using the four-point bending test. Three groups of samples have been investigated, all groups containing 30 samples of the same type of softwood spruce (*Picea abies* – C16), as it will be shown in the following sections.

2. METHODOLOGY

Softwood (*Picea abies* – C16) samples with a cross-section of $50 \times 50\ \mathrm{mm}^2$ and length of 4 m had been procured from the local market. The average mechanical properties for the samples were 52.29 MPa for *MOR*, 11.2 GPa for *MOE*, with an average density equal to $366\ \mathrm{kg\ m}^{-3}$. The 4 m long pieces had been cut into 1 m samples, and the samples were grouped in group A, B and C. Group A contained samples tested under natural conditions (room *T* is 23.8% and *RH is* 29.3%), group B contained samples submerged in water (pH 6.5, total hardness 50 CaO $\mathrm{mg\ L}^{-1}$) for a 7 days until the fully saturated state [15], and group C has been tested with the same conditions as group B, but glazed by a coating material previous to submerging. There are layers of Sadolin Extra, which is an outdoor silk-gloss thick glaze material that protects and decorates outdoor wooden surfaces, were applied. According to the manufacturer, it provides long-lasting protection against the weather and the sun UV radiation. It has a water-repellent effect, and it is absorbed by the wood.

The four-point bending tests have been conducted according to the Hungarian specifications (MSZ EN 408:2011 [16] and MSZ EN 384:2010 [17]) using a displacement control system, where the load increment was controlled, its speed was set for $5\ \mathrm{mm\ min}^{-1}$. Before starting the test, the environmental *T* and *RH* were measured. The surface *MC* of each sample was measured using a Testo 606-1 device. According to the standards, the samples were assembled in the center of the supports; the distance between the two supports was 900 mm with a span of loading equal to 300 mm. The testing machine (Instron static hydraulic – Satec series) was connected to a computing system which allowed measuring the load and the deflection every 0.1 s.

Figure 1a shows the load analysis for each wood sample, Fig. 1b shows the force versus displacement curves generated by the testing machine. The bending moment value is equal to half of the applied load (*F*/2) multiplied by the loading span distance (*a*), which is equal to 300 mm. Stress (σ), *MOR*, and strain (ε) values of each sample can be calculated using the following equations respectively:

$$\sigma = \frac{3Fa}{bh^2}, \tag{1}$$

$$MOR = \frac{a(F_{\max}/2)(h/2)}{bh^3/12} = \frac{3F_{\max}a}{bh^2}, \tag{2}$$

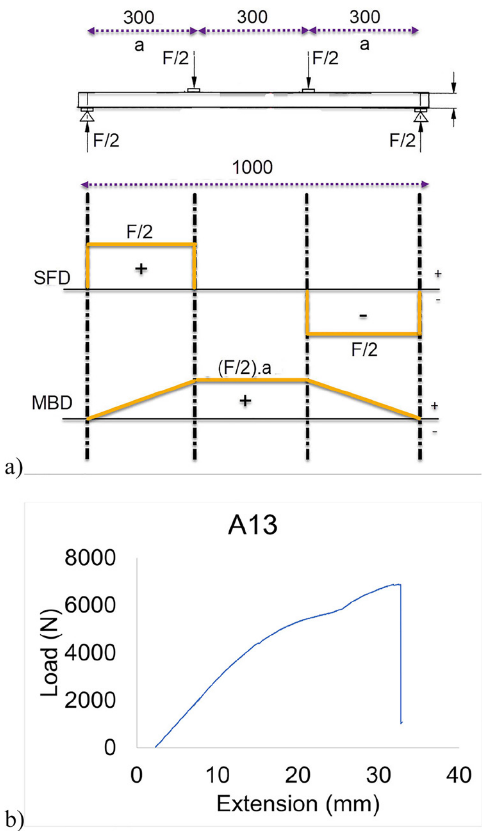

Fig. 1. a) Load analysis of the testing sample; b) load vs. displacement curve generated by the testing machine for sample A13

$$\varepsilon = \frac{h}{2R}, \tag{3}$$

where h and b are the depth and width of the cross section, and R is the radius of the measured curvature, using the displacement values.

To calculate the accurate *MC*, a 9 cm long piece was cut from each sample to be weighted in the current phase, its mass was denoted as m_1. The 9 cm samples were dried using a furnace until three consecutive stable weight readings were obtained, denoted as m_{dry}. Thus, *MC* equals to:

$$MC = \frac{m_1 - m_{dry}}{m_{dry}}. \tag{4}$$

To obtain an accurate comparison between the samples, the *MOE* and *MOR* values were converted to an MC value equal to 12% according to ISO 13061-3:2014 [18] and ISO 13061-4:2014 [19] using the following equations:

$$MOE_{12} = \frac{MOE}{1 - \alpha(MC - 12)}, \tag{5}$$

$$MOR_{12} = MOR(1 + \beta(MC - 12)), \tag{6}$$

where α and β are the correction factors, equal to 0.02 and 0.04 respectively.

3. RESULTS AND DISCUSSIONS

3.1. Fracture behavior of samples

The very first observations on the fracture behavior of the samples could already be done on the basis of their failure modes. Group A samples showed brittle behavior with different failure modes shown in (Fig. 2). Simple tension failures occurred in 27% of the samples, 3% of the samples had brash tension failure, 13.5% of the samples had buckling failure, and 56.5% of the samples had a cross-grained tension failure. Group B samples showed buckling failure in most of the cases (83% of the samples) combined with few millimeters crack width spread along the sample. The remaining 17% of samples had cross-grained tension failure. In group C, 63.5% of the samples had cross-grained tension failure, 23.5% of the samples had buckling failure, and 13% of the samples had simple tension failure.

The variation of failure modes in group A can be explained by the fracture behavior of the wood in its natural state, which is considered a brittle material. On the other hand, the fracture behavior in the timber sample changed to ductile or semi-ductile behavior as the MC grew, increasing the possibility of achieving high displacements without significantly reducing the material strength [20]. In case of group C, the samples absorbed the glazing material, thus protecting the wood cells from the moisture impact and maintaining the brittle behavior in most of the samples. Generally, ductile behavior is better than brittle behavior because ductile materials can undergo extensive plastic

Fig. 2. Failure modes found during the test for the case of group A, a) simple tension failure; b) cross-grained tension failure; c) brash tension failure; d) buckling failure

deformation before failure, making them more resistant to sudden fractures or failures. Furthermore, ductile materials provide warning signs of impending failure through visible deformations, enabling timely repairs or replacements to prevent catastrophic incidents. The fracture behavior of wood varies depending on species, however, the main controlling factor for every wooden species is the *MC*. Reaching ductility in timber means high *MC*% thus high strain value, however this results in very weak resistance and strength against static and dynamic loads, while the brittle behavior gives high strength values and an acceptable strain value. The best scenario happens in group C where both resistance and deformation capacity increase. This explains why different design annexes prefer brittle behavior in timber elements, and the importance of choosing the appropriate glazing (covering) materials.

3.2. Mechanical properties of the samples

Figure 3 shows the stress versus strain diagram for the maximum and minimum strength of rupture samples from

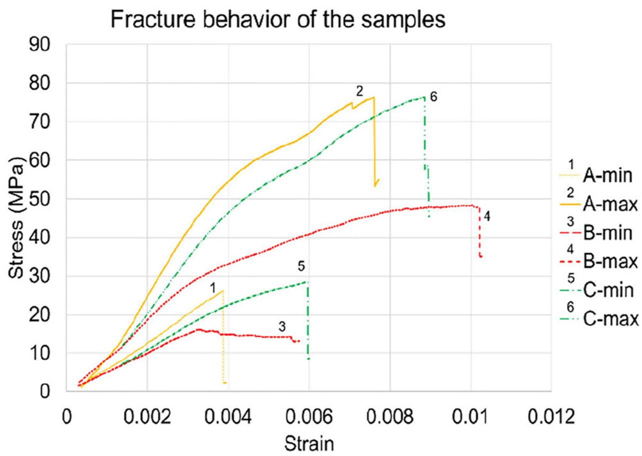

Fig. 3. Stress vs. strain diagram for maximum and minimum strength of rupture of tested groups

each group. As it is shown in Fig. 3, group B samples deform (elongate), recording more strain values with lower stress values compared to group A and C, and have a nonlinear elastic deformation referring to the increase in *MC*, which explains why the buckling failure was dominated in group B.

The cracks width in group A and C were ranging between 5 and 70 mm, however for group B, the cracks width was around 5 mm, since the buckling failure is harder to be detected. This can be explained by the differences in the failure modes between the testing groups, which reflect the danger behind the *MC* increase through exposure to climate components. With the increase in strain (increasing ductility), the *MOR* and *MOE* values are decreasing (see Table 1). This failure happens in case of compression elements such as columns and bracing elements, considered as main structural parts in roofs and towers.

The density and *MC* values under natural conditions and after the wetting are shown in Table 2. Higher density wood samples absorb higher amount of water under natural conditions and also after full wetting, which remains true also after the surface treatment of the samples with a coating layer. Additionally, non-coated samples *MC* increased by 1.7 times in average after full wetting, however coated sample *MC* has increased only by 2 times.

The values of *MOR* and *MOE* are influenced by the density of the samples, lower density values are accompanied by lower *MOR* and *MOE* values. Figure 4 shows the density vs. the modulus of rupture for all the measured samples.

Table 3 shows the mechanical properties of the tested samples. The values for Group A are the corrected for *MC* equal to 12%, while the group B and C samples were measures in fully saturated state.

Table 1. Strain and *MOR*, *MOE* correlation coefficient (*R*)

	Group A	Group B	Group C
$R_{strain\ \&\ MOR}$	0.6998	−0.2078	0.7396
$R_{strain\ \&\ MOE}$	0.5044	−0.0945	0.3696

Table 2. Density and MC values for the studied groups of samples

	Group A	Group B	Group C
Density (kg m^{-3})	335–512	263–399	303–500
MC(%) natural conditions	9–14	17–35	2.5–19
MC(%) after wetting	–	34–65	14–30

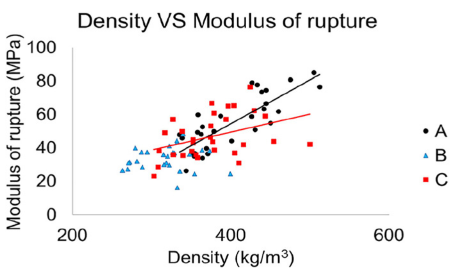

Fig. 4. Density vs *MOR*

Table 3. Mechanical properties results based on four points bending test

		Mean values (30 samples)	Standard deviation (σ)
Group A	MOR_{12} (MPa)	52.29	14.32
	MOE_{12} (GPa)	11.21	2.68
Group B	MOR_{Sat} (MPa)	33.86	16.23
	MOE_{Sat} (GPa)	7.20	5.05
Group C	MOR_{Sat} (MPa)	46.73	12.78
	MOE_{Sat} (GPa)	9.59	2.03

As it is shown in Table 3, the increase of the *MC* in group B leads to a massive decrease in the mechanical properties of the wood samples, the degradation (*MOR* and *MOE* values decrease) caused by the full water submerge was 35% compared to the room temperature tested group A. In the case of group C, the degradation values were 11% and 15% for *MOR* and *MOE*, respectively.

Figure 5 shows the *MOR* values for the A, B and C groups of samples, highlighting the superior strength of the samples in their natural state (Group A), the pronounced weakening of fully saturated samples (Group B), and the transitional nature of the glazed samples (Group C) positioned between the two extremes. When wood samples are surface treated, their mechanical properties are much less influenced by the *MC*, even for a full water saturation state which is an extreme circumstance. Therefore, an optimum state of ductility increases of the wood, and only low mechanical deterioration can be reached by the proper choice of a surface treating material. The measurements offer valuable insight into the effects of moisture content on the rupture characteristics (Fig. 5) and modulus of elasticity of the tested samples, aiding the understanding of material behavior under different moisture content conditions.

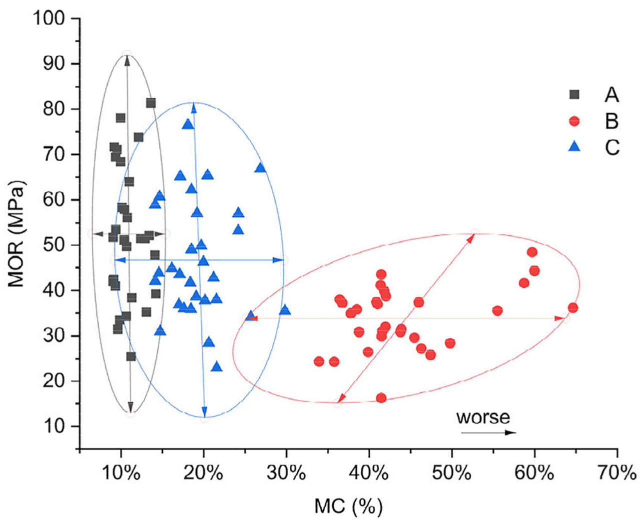

Fig. 5. MOR vs. *MC* 95% confidence ellipse graphs for the three groups of tested samples

3.3. Statistical evaluation of the test

The *MOR* and *MOE* values of the three groups of tests showed Poisson's distribution (see Figs 6 and 7).

In Figs 6 and 7, the *MOR* and *MOE* values of group B and C samples has shifted to the left compared to group A samples, indicating a degradation of the mechanical properties. Figure 6 shows that the probability of having a sample with *MOR* equal to 52 MPa in group A is almost equal to 6% while it is 4.2% in group C. For group B to have the same *MOR* value, the probability is almost zero. Figure 7 shows similar degradation results regarding the *MOE* values. To have a sample where *MOE* equals 11 GPa in groups A and C, the probability equals 12%. Attaining the same value in group B has a probability of 6%. All these statistics prove the positive impact of painting the timber element to protect it from weathering factors, especially the water impact. Using linear regression and calculating the correlation factors as an average in all groups, the MC increase has a greater negative impact on the *MOR* values with a correlation factor equal to −25% than the *MOE* values with a correlation factor equal to −18%.

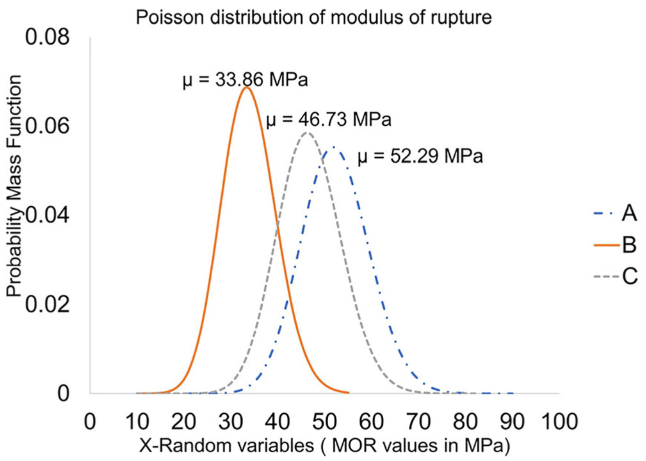

Fig. 6. Modulus of rupture representation in terms of Poisson's distribution

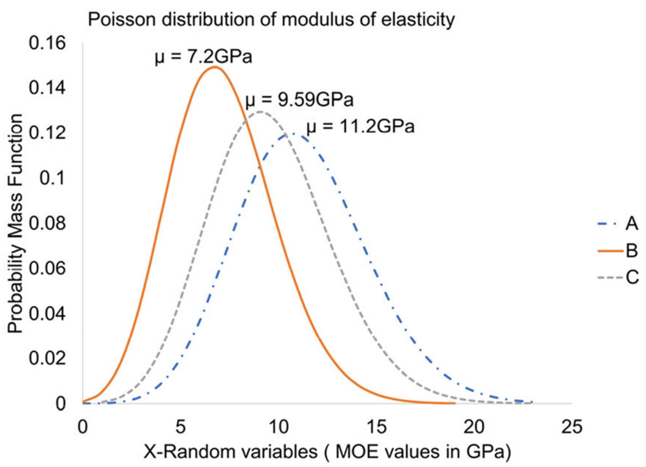

Fig. 7. Modulus of elasticity representation in terms of Poisson's distribution

4. CONCLUSIONS

In construction, wood has started to be rediscovered as a renewable material. However, its short lifetime compared to concrete, limits its applications. Therefore, understanding the degrading effects of the environmental and climate conditions on mechanical properties is of great importance. Based on the performed laboratory tests and the results of the statistical analysis, it can be concluded that the wood moisture content has a significant degrading influence on its mechanical properties; however the surface treatment of the material can significantly diminish the deteriorating effects of the moisture.

The paper discussed the impact of extreme *MC* conditions on modulus of rupture and modulus of elasticity of the pine softwood. The increase in *MC* decreases the bending strength and the modulus of elasticity to one-third of their original values perpendicular to the grain direction. In line with the Eurocode 5 requirements, the glazing guaranteed the brittle behavior by decreasing the buckling failure, which is common in ductile elements. In the case of wood samples tested under natural conditions the number of buckling failures was 4, which increased to 18 for fully wet ones. When surface glaze was applied, the buckling behavior decreased again to 7 samples. Therefore, the positive impact of the glazing even on fully water submerged samples could be proved. The glazed submerged samples' *MOR* and *MOE* increased by 27.5% and 26.1% compared to the unglazed submerged group.

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