THE EFFECT OF TIMBER PROPERTIES ON THE BEHAVIOUR OF BENDING ELEMENTS UNDER LOADING

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Abstract

Timber structure is a very complex system with its own specific character that causes a lot of difficulties for designers to predict its precise behaviour under loading. Timber construction behaviour under load is affected by many factors that in most cases influence timber constructions in a negative manner. Part of these influencing factors are properties of material, the other are components of the environment where the timber construction is located.

This paper presents the results of experimental research where seventeen softwood *(Pinus Sylvestris)* timber beams of rectangular cross section were tested in four point bending under long-term load in uncontrolled microclimate conditions (unheated building, all year round weather in the region of Latvia). Values of mechanical properties (modulus of elasticity), physical properties (density, amount of latewood, number of annual rings in 1 cm of wood) were measured at the start of the test; while monitoring of moisture content of wood, relative humidity and air temperature were performed simultaneously for the whole period of test.

It has been observed that the main factors that significantly influence timber beam behaviour during period under load in natural climatic conditions are modulus of elasticity (MoE), density of wood and number of annual rings per 1 cm of wood. Amount of latewood showed an insignificant impact on timber beam behaviour under load.

Key words: Timber, beams, behaviour, MoE, density.

Introduction

Molecular structure of wood is a very complex system with uneven distribution of molecules. J. Bodig and B.A. Jayne (1982) found that wood has very manifold physical and mechanical properties because of its anisotropy and fibrous structure which needs to be taken into consideration when using wood in construction.

Strength and stiffness of timber structures depend on many factors. The biggest impact on the strength properties of timber is provided by MoE, density of wood, number of annual rings per 1 cm of wood, as well as moisture content, amount of latewood and other factors.

The modulus of elasticity is one of the most important elastic constants of the material and parameter of its quality (Dinwoodie, 2000). Research of F. Divos and T. Tanaka demonstrated that the most important strength predictor parameter is MOE. S.Y. Zhang (1997) proved that modulus of elasticity is poorly and least linearly related to the wood density.

Fibers are the principal element that is responsible for the strength of wood (Panshin and Zeeuw, 1980). The presence of defects such as checks, cross grain, pitch pockets, shakes, and wrap causes a considerable reduction in the mechanical properties of the timber (Dinwoodie, 2000).

Density and microfibril angle (indicators of strength and stiffness) are the most important determinants of wood quality. Wood density indicates the amount of actual wood substance present in a unit volume of wood (Cave and Walker, 1994). A.J. Panshin and C. de Zeeuw (1980), D.J. Cown (1992), J.M. Dinwoodie (2000) reported that density is a general indicator of cell size and is a good predictor of strength, stiffness and other properties. Basic density is closely related to structural timber strength (Harvald and Olesen, 1987). Wood density is affected by the cell wall thickness, the cell diameter, the earlywood to latewood ratio and the chemical content of the wood (Cave and Walker, 1994).

Timber consists of earlywood and latewood where latewood forms cells with thicker walls, which means that increasing amount of latewood will increase the density and strength of the timber (Illston and Domone, 2004).

Since the behaviour of timber beams under load is influenced by many factors, the aim of this research is to give a comprehensive view about some mechanical and physical influencing factors of timber beams in a natural environment under load.

Materials and Methods

The test was started in December 2011 in Jelgava, Latvia, and was carried out in a newly constructed house which is not currently inhabited. This house was not heated in the winter period; therefore, the climatic conditions were not controlled in any way that allowed checking the timber beam behaviour under load in variable climatic conditions of ambient humidity and temperature.

The experimental test represents a loading of seventeen (free of knots) pinewood (*Pinus sylvestris* L.) beams in four-point bending. The bending test setup and static model are given in Figure 1. The timber beam cross section nominal dimensions (height and width) were 60 mm and 30 mm respectively.

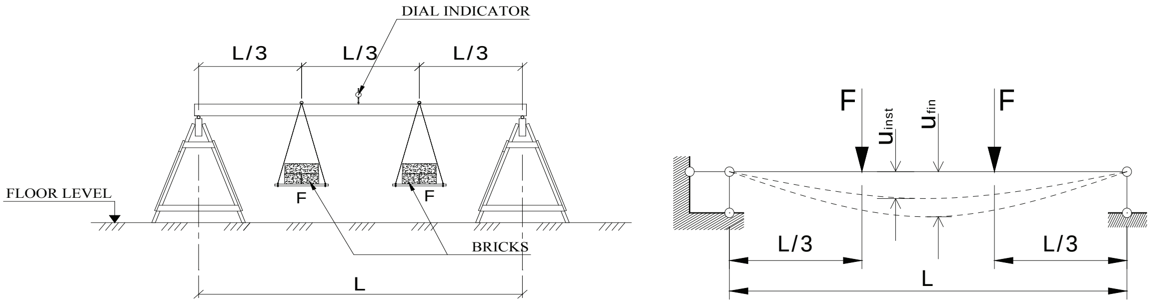

Figure 1. Long-term bending test setup and static model.

Concentrated forces were represented by clay and silicate bricks which were suspended on timber beams. The deflection measurements were made with dial indicators. Measuring precision of indicators – 0.01 mm. Measuring diapason of indicators – 50 mm. The dial indicators were placed in the middle of the span on the compressed side of the beam. The environmental climatic condition parameters were recorded once during the day. Temperature (T, °C) in the room and outdoors was fixed with mercury-in-glass (Hg) type thermometers.

Determining Modulus of Elasticity

Theoretical MoE in four-point bending was calculated after registering instantaneous elastic deflection (u_{inst}) immediately (1 minute) after loading. Theoretical MoE of rectangular cross-section elements, which are loaded in bending with two symmetrical concentrated forces, was calculated using equation (1):

$$MoE = \frac{F \cdot a}{4 \cdot b \cdot h^3 \cdot u_{inst}} (3 \cdot L^2 - 4 \cdot a^2), \tag{1}$$

where: F – sum of two concentrated forces, kN;
a – distance from support to concentrated force, cm;
L – timber beam span, cm;
b – width of cross section, cm;
h – height of cross section, cm;
u_{inst} – instantaneous deflection, cm.

Measuring wood density

The density of timber beams (ρ) was determined following the methodology of the standard LVS EN 408:2003 and LVS EN 384:2004 before the start of the test. The density of timber beams (ρ) was determined by oven-dry method using samples with a full cross section dimensions (60 mm x 30 mm x 30 mm) free from knots and resin pockets from the both ends of timber beams. Samples were oven-dried at 103 °C ± 2 °C until constant mass was achieved. Constant mass is attained when the results of two successive weighings, carried out at an interval of 6 hours, do not differ by more than 0.1% of the mass of the test piece. Dimensions of the test pieces were measured before oven-drying and after drying with slide gauge with an accuracy of 0.1 mm.

Determining amount of latewood and number of annual rings in 1 cm of timber

Two specimens with dimensions of 20 x 20 x 20 mm were cut out from a cross section of every timber beam. On the plane of the cross section in the radial direction, boundaries of whole annual rings were marked with a section of 20 mm. Number of annual rings in that section were counted (N). Dimensions (l) between end marks of whole annual rings were measured with an accuracy of 0.5 mm. Width of latewood (b_l) in every annual ring was measured with accuracy of 0.1 mm. Number of annual rings (n) per 1 cm of timber cross section were calculated using equation (2):

$$n = \frac{N}{l} \tag{2}$$

where: N – number of whole annual rings;
l – dimension between end marks of whole annual rings, cm.

Amount of latewood (m) percentage was calculated with accuracy of 1% using equation (3):

$$m = \frac{\sum b_l}{l} \tag{3}$$

where: Σb_l – sum of latewood in one specimen between end marks of whole annual rings, cm;

The correlation was provided between the main timber beam long-term loading behaviour affecting factors – MoE, amount of latewood, annual rings in 1 cm of wood, density, timber beam span to height ratio (L h^{-1}), moisture content of wood and other variables.

A regression analysis was made between the most important timber beam behaviour under load affecting factors; and coefficient of determination R^2 was calculated, too.

Table 1

Summary of timber beam properties

Timber beam marking	Span L, cm	Distance between supports a, cm	Force F, kN	Density of wood ρ, k gm^{-3}	MoE $E_{app.inst}$, kN cm^{-2}	Amount of latewood m, %	Number of annual rings in 1 cm	Inst. defl. u_{inst}, cm	MC w, %	L h^{-1}	MoE ρ^{-1}
KS-4.10	150	50	0.31	533	948.69	48	5.90	0.80	31	26.00	1.78
KS-4.9	150	50	0.31	457	514.42	57	3.40	1.30	26	25.40	1.13
KS-4.8	150	50	0.31	485	610.26	41	4.80	1.20	32	25.67	1.26
KS-4.7	150	50	0.31	572	1509.26	50	6.00	0.50	32	25.86	2.64
KS-3.10	132	44	0.40	526	1025.69	28	4.50	0.60	32	22.50	1.95
KS-3.9	132	44	0.40	577	916.65	52	7.40	0.70	29	22.54	1.59
KS-3.8	132	44	0.40	484	506.73	45	3.50	1.20	19	22.59	1.05
KS-3.7	132	44	0.40	499	781.77	50	5.10	0.90	20	22.69	1.57
KS-3.5	132	44	0.40	437	797.15	42	2.70	0.79	20	22.58	1.82
KS-3.3	132	44	0.40	450	898.89	44	4.30	0.77	29	22.80	2.00
KS-3.2	132	44	0.40	607	1294.89	44	7.20	0.48	32	22.59	2.13
KS-3.1	132	44	0.40	534	1324.58	45	8.00	0.48	33	22.59	2.48
KS-2.5	120	40	0.20	478	647.18	49	4.50	0.35	19	20.47	1.35
KS-2.4	120	40	0.20	545	1255.03	49	6.00	0.18	19	20.67	2.30
KS-2.3	120	40	0.20	518	962.54	46	8.30	0.24	19	20.92	1.86
KS-2.2	120	40	0.20	455	591.56	48	3.30	0.38	19	20.47	1.30
KS-2.1	120	40	0.20	609	1170.93	36	6.40	0.19	19	20.71	1.92

Results and Discussion

Results of mechanical and physical properties of timber beams at the start of the test are summarized in Table 1. Results of all timber beams show that specimens that are used in test have various mechanical and physical properties.

Modulus of elasticity varied in the range from 506.73 kN cm^{-2} to 1509.26 kN cm^{-2} with a mean value of 926.84 kN cm^{-2} with a coefficient of variation (COV) of 33%. The value of COV of 33% for MOE is high even for the wood where good COV is in within 10 to 15%.

Density of timber beams varied in the range from 437 kg m^{-3} to 609 kg m^{-3} with a mean value of 516 kg m^{-3} and with a COV of 10%.

One of the most important timber physical factors from the results of experimental research is the number of annual rings per 1 cm, which presented values from 2.7 to 8.3 with a mean value of 5.4 with a COV of 32%. The higher the number of annual rings per 1 cm, the better the quality of structural element – timber beams having higher strength and stiffness as well as behaviour under load is much better. This fact is testified by the good positive coefficient of correlation (0.76 and 0.68) between the number of annual rings, density of wood and MoE (see Table 2).

The ratio of modulus of elasticity to density (MoE ρ^{-1}) helps to counteract the effects of the large variety of wood. Ratio MoE ρ^{-1} varied in the range from 1.05 to 2.64. This ratio is a good predictor of strength and stiffness of timber beams. Correlation analysis between MoE ρ^{-1}, density of wood and the number of annual rings per 1 cm of wood showed an average positive relationship (0.55 and 0.57) that approximately allow to predict the strength properties of timber beams used in this test.

Moisture content (MC) of timber beams at the start of the test varied in range from 19% to 33% with a mean value of 25% with a COV of 24%. Relative deformation of timber beams are directly connected with MC of wood and temperature of the environment. The increase in strength and stiffness when moisture content of wood is relatively stable, can be explicitly seen in Figure 5. Increase of relative deformation in time at lower MC is much smaller (from the 61st day of the test till the end of the test) than it was at the start of the test (from 1st to the 61st day of test) when an active drying period of timber beams

Table 2

Correlation between main timber beam properties affecting factors

	Density of wood	MoE	Amount of latewood	Number of annual rings in 1 cm	Inst. defl.	MC	L h^{-1}	L u^{-1}	MoE ρ^{-1}
Density of wood	1								
MoE	0.76	1							
Amount of latewood	-0.17	-0.19	1						
Number of annual rings in 1 cm	0.76	0.68	0.02	1					
Inst. defl.	-0.49	-0.62	0.19	-0.53	1				
MC	0.29	0.41	-0.18	0.29	0.22	1			
L h^{-1}	-0.08	-0.01	0.18	-0.16	0.70	0.65	1		
L u^{-1}	0.49	0.51	-0.12	0.47	-0.85	-0.41	-0.62	1	
MoE ρ^{-1}	0.55	0.96	-0.20	0.57	-0.59	0.39	-0.01	0.44	1

was observed together with a fast decrease of air temperature.

Amount of latewood in all specimens showed values from 28% to 50% with a mean value of 46% with a COV of 14%. Amount of latewood presented very low relationship with other examined factors. T. Kubo and S. Jyodo (1996) stated that amount of latewood in the growth ring largely determines the density of the wood, which in turn affects its strength and stiffness, however, the results of this test do not approve this relationship (see Table 2). Coefficient of correlation r presented low relationships between amount of latewood and all other inspected factors.

Correlation between main affecting factors was provided and the results of analysis are summarized in Table 2.

The relationship between instantaneous deflection and all other factors was variable. Test results showed a good correlation with span to height ratio L h^{-1} (0.70); an average correlation with density (-0.49), MoE (-0.62), the number of annual rings (-0.53), MoE ρ^{-1} (-0.59); low correlation with amount of latewood (0.19) and MC (0.22). From these results we can conclude that instantaneous deflection of timber beams mostly depends on span to height ratio and only after that deflection are influenced by mechanical and physical factors.

Linear regression analysis between main mechanical factor MoE and physical properties of timber beams, and coefficient of determination R^2 are illustrated in Figure 2.

Regression analysis between MoE and other influencing factors showed that only two factors (density of wood and number of annual rings per 1 cm of wood) have a reckonable influence on MoE in terms of this test. Coefficient of determination R^2 recorded values of 0.51 and 0.49 that is an average tight relationship. The relationship between MoE, MC and amount of latewood showed low values of coefficient of determination R^2 – 0.158 and 0.0154 respectively, so those two factors have no reckonable influence on MoE in terms of this test.

To give general overview about behaviour of all timber beams under load during the period of test, the average curve of relative deformation versus time is given in Figure 3. It has to be taken into account that on the 61st day of the test (peak of the relative deformation curve) half of attached load was removed to simulate real climatic conditions of nature with doubled amount of permanent load for the winter period. This operation was made because of the requirements of the creep test under natural environment.

The conception of that how deformation of timber beams under load is influenced by MC of wood and temperature of the environment is illustrated in Figure 4. Deformation of timber beams increases together with drying of wood and fluctuations of temperature till the 61st day of the test when half of the attached load was removed, and persistent increase of temperature and period of stable MC were recorded. Simultaneously with constant period of MC, increment of relative deformation was low. We can conclude that the behaviour of timber beams under load is significantly affected by variations of MC and temperature. I have not studied influence of stress level on behaviour of timber beams in this test, but fast increment of deformation in time span when higher load was attached prove that the stress level has a significant influence on timber beam behaviour under load.

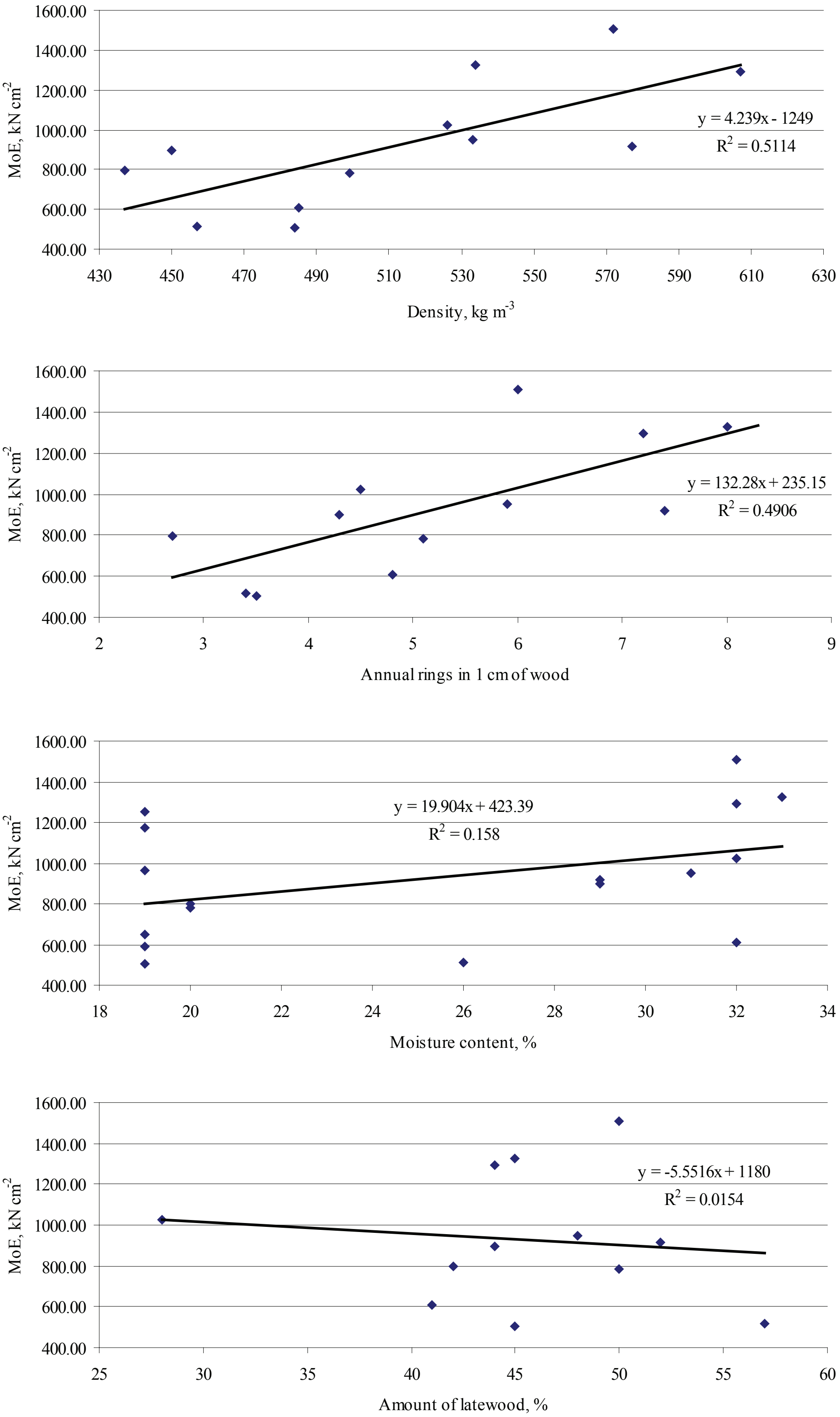

Figure 2. Relationships between MoE and main timber beam physical properties.

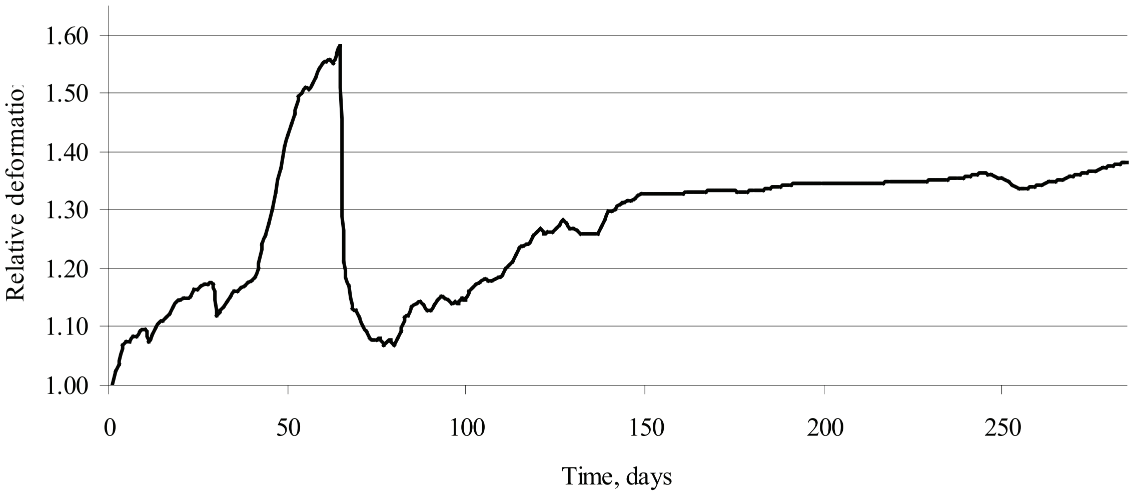

Figure 3. Average curve of relative deformation versus time.

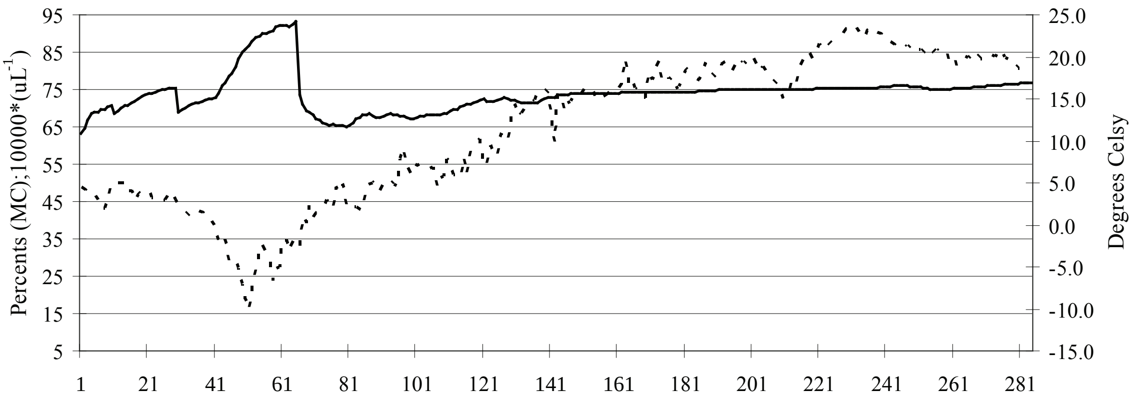

Figure 4. Average relative deformation, moisture content and temperature versus time.

Conclusions

1. This research gives a general insight into the behaviour of bending elements under load in natural environmental conditions and main behaviour influencing factors. Part of these influencing factors are mechanical and physical properties of material (MoE, density, amount of latewood, number of annual rings per 1 cm of wood and MC), others are a component of the environment (temperature) where bending elements are located.
2. The most important mechanical and physical influencing factors of bending elements are MoE, density of wood and number of annual rings in 1 cm of wood. The higher is the value of every of those three factors, the better is the behaviour of timber beams under load.
3. Instantaneous deflection of timber beams for the most part is negatively influenced by increasing span to height ratio (L h^{-1}) and afterwards by material properties – MoE, density of wood and number of annual rings in 1 cm of wood. Amount of latewood and MC in terms of this test have a low impact on the instantaneous deflection of timber beams.
4. Fluctuations of MC of wood and temperature of the environment have a reckonable negative influence on the behaviour of bending elements. In the period of variable environment temperature and drying of wood, increment of deformation was much bigger than it was in the span of time of stable temperature and much lower level of MC of wood.

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