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Influence of Wood Moisture on Strength and Elastic Modulus for Pine and Fir Wood Subjected to 4-point Bending Tests

Anna Pestka [1], Paweł Kłosowski [1], Izabela Lubowiecka [1], Marcin Krajewski [1]

[1] Gdańsk University of Technology, 11/12 Gabriela Narutowicza Street, 80-233 Gdańsk, Poland

markraje@pg.edu.pl

Abstract. The main purpose of this research paper was to determine the influence of the wood moisture on the strength and elastic modulus of pine and fir wood specimens subjected to the 4-point bending tests. Six bending tests for each wood species and for two different moisture level have been performed. Then, the advanced statistical analysis of the results has been carried out. On the basis of the obtained results, it has been noted that growth of the wood moisture significantly affects the reduction of the tested strength and elastic modulus. It has been noticed that the values of the bending strength of the wet specimens (the wood moisture approximately 29%) decreased by more than 40% in relation to the dry specimens (the wood moisture approximately 10%).

1. Introduction

Civil engineering wood is still an important constructional material due to two main reasons. Firstly, because of the growing interest of architects in the use of today's fashionable, natural materials. Secondly, due to the need of restoration of wooden historical buildings, especially of the heritage value. The old buildings often require the rehabilitation and restoration of old structures by the repair or reinforcement of existing elements to ensure the safety of the wooden structure.

On the other hand, wood is a material difficult to analyse compared to steel or concrete due to its heterogeneity. The literature often classifies wood as a highly anisotropic material and also heterogenic due to the natural defects such knots, slopes of grain or shakes decay (see e.g. [1-3] among others). It also reports that its mechanical properties, in particular in terms of strength and elasticity, depend primarily on moisture, temperature and aging [4, 5].

The mechanical properties of wood in bending have been largely investigated before and the majority of research works agreed on the fact that the bending strength and bending stiffness remain almost unchanged over the time. The highest bending stiffness and bending strengths reductions are reported for structural timber, which is affected by the in-service condition, such as duration of load, state of conservation and dismantling damages as widely described in [5]. Thus, in our study we focus our attention on changes of the mechanical parameters, such as the strength and stiffness of wood, with respect to changes of its moisture. The analysis is undertaken for pine and fir wood subjected to 4-point bending tests.

An advanced statistical analysis of the experimental results is performed here to specify the changes of the tested values depending on the wood moisture. This type of data becomes significant while one needs to consider uncertainties of the mechanical characteristics of a material into an overall analysis like reliability of a timber structure (see e.g. [6, 7]) or a proper finite element modelling within stochastic framework [8], which with the growing interest in wooden buildings may become more and more popular. This type of results is not provided frequently in literature and if it is, the results may depend on the region the wood comes from. In this paper, the analysis is performed for wood coming from the south of Poland, a region where the wood is widely used in historic structures as well as in the contemporary architecture.

2. Experiment description

The experiments have been performed for two species of wood: pine and fir. The tests have been performed on specimens of 400-402 mm length. The cross-section dimensions of the specimens have been approximately 40 mm by 20 mm (figure 1).

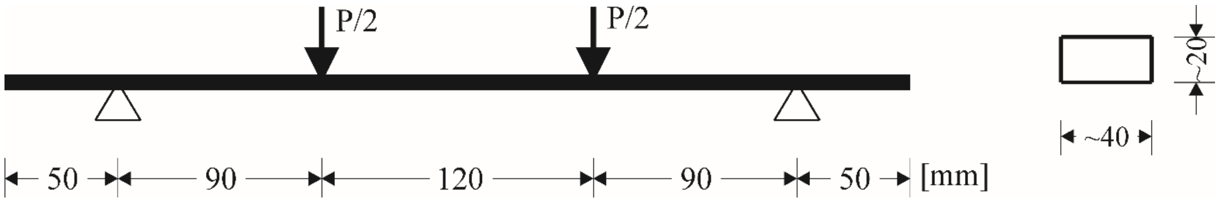

Figure 1. The 4-point bending tests - experimental stand and dimensions of specimens

The tests have been carried out on Zwick/Roel Z400 testing machine with 50 kN force head. The mechanical extensometer has been applied to reduce the experimental error. The experiment scheme and the laboratory stand for the 4-point bending tests is shown in figures 1 and 2. The location of the sensor arms is presented in figure 3.

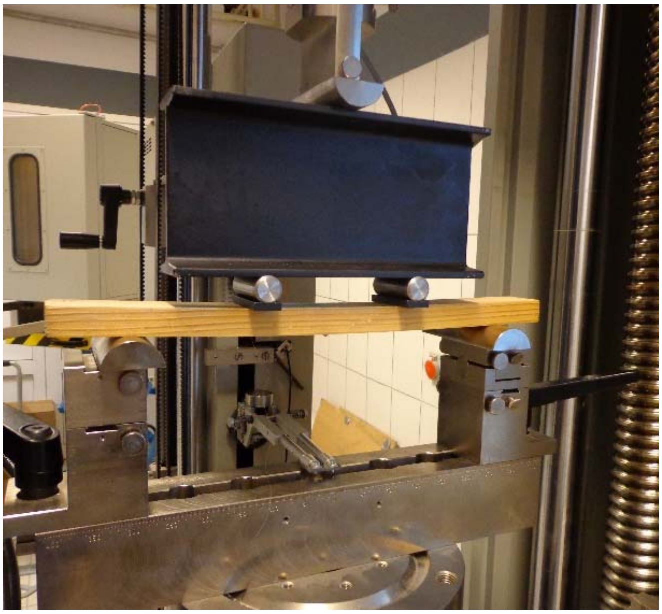

Figure 2. The 4-point bending tests - experimental stand

Figure 3. The 4-point bending tests - location of the sensor arms

Twelve tests of 4-point bending have been carried out for both kinds of wood. All specimens have been stored at room temperature prior to testing. Six samples of both wood species were dipped in water to increase wood moisture (wet specimens) for 24 hours before the test. The dimensions, wood moisture and weight have been measured before testing. The results including time, force and displacement measured by the extensometer have been computer recorded with the approximate frequency of 3000 sampling points per each tests.

3. Identification of mechanical properties

On the basis of the experimental data, the strain-stress functions have been determined. Next, the linear deformation range has been estimated for each test. Then, the values of the elastic modulus have been calculated. Generally, the stress-strain functions are linear for the strain range of between about 0.09% to 0.28%. The strain-stress functions for each test are presented in figure 4 for the pine wood and in figure 5 for the fir wood.

The values of the elastic modulus *E* along the wood threads in each test has been determined by performing the linear approximation using the least-squares method in the range specified above [9, 10]. The values of the bending strength have been calculated as the quotient of the bending moment and the section modulus. The obtained values of the elastic modulus and the bending strength are shown in table 1.

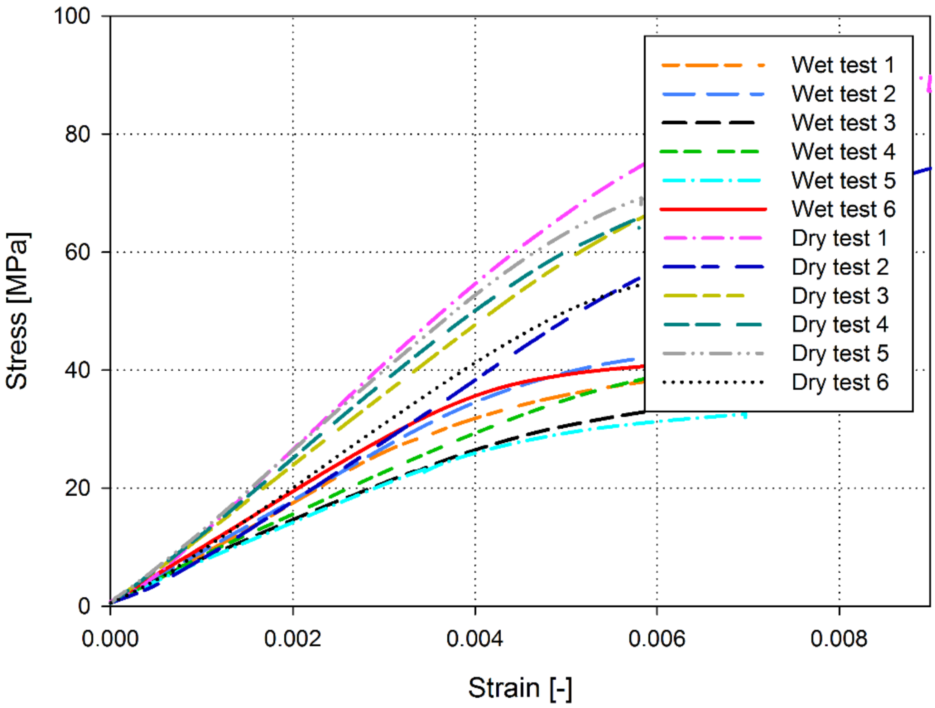

Figure 4. Stress-strain functions for pine wood

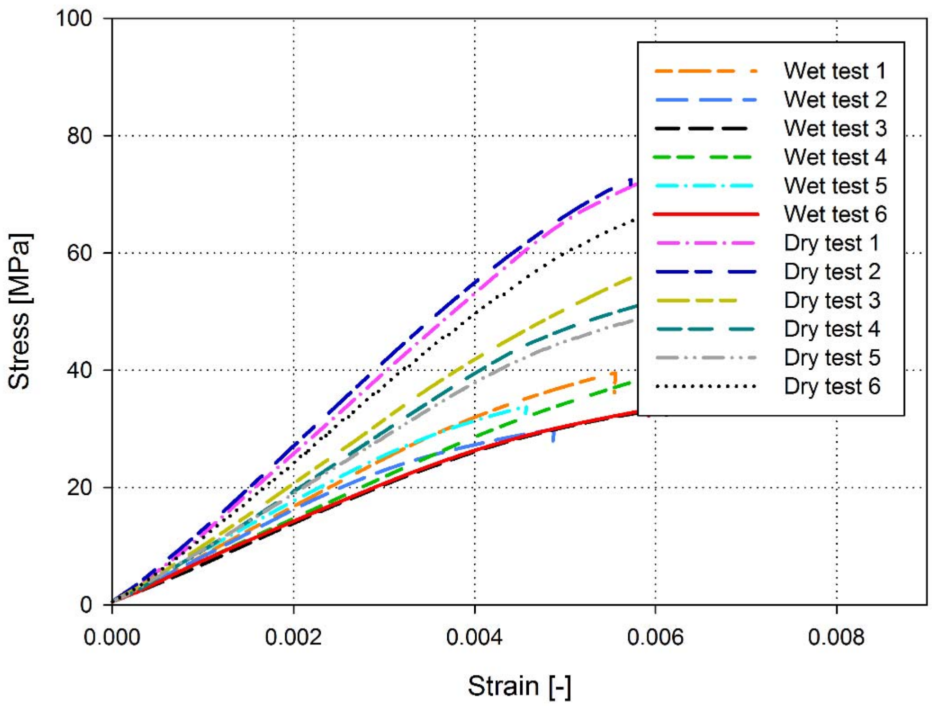

Figure 5. Stress-strain functions for fir wood

Table 1. Values of elastic modulus and bending strength for each test

	Cross-section dimensions [mm]	Length [mm]	Weight [g]	Moisture [%]	Elastic modulus [GPa]	Bending strength [MPa]
Pine wood (dry specimens)	39.7 × 19.8	400	168	7.0	14.4	90
	39.4 × 19.8	400	148	6.2	10.2	78
	39.3 × 19.9	400	167	7.2	11.9	71
	40.4 × 20.3	401	185	11.6	12.9	66
	39.9 × 20.0	402	171	12.6	13.6	69
	39.3 × 20.0	401	147	13.9	10.7	58
Pine wood (wet specimens)	39.6 × 19.9	400	224	24.0	8.8	41
	39.9 × 20.5	401	169	18.0	8.7	45
	39.7 × 20.4	400	177	23.2	6.5	36
	39.8 × 20.2	401	150	18.6	7.1	42
	39.4 × 20.3	401	235	26.0	6.5	33
	39.7 × 20.3	400	173	18.8	9.5	41
Fir wood (dry specimens)	39.1 × 19.8	400	142	7.4	13.7	73
	39.2 × 20.0	400	139	9.0	14.3	73
	40.2 × 20.0	400	144	8.3	10.3	63
	40.0 × 20.0	401	139	11.8	10.1	51
	40.3 × 20.3	400	143	13.0	9.5	50
	40.0 × 19.8	401	148	15.3	12.9	70
Fir wood (wet specimens)	39.7 × 20.0	402	202	34.2	8.3	49
	40.7 × 20.0	401	223	40.8	7.8	30
	39.6 × 20.4	402	189	41.3	6.8	34
	40.0 × 20.6	401	188	30.6	7.1	41
	39.9 × 20.3	402	180	43.3	8.5	34
	40.3 × 20.5	401	182	37.5	6.6	33

4. Statistical analysis

The statistical analysis has been performed for the obtained results of the elastic modulus and the bending strength. Both species of the wood in dry and wet state were considered and the following quantities have been calculated [11]:

- measures of position: arithmetic average of the sample $\overline{x}$ and median m_e,
- measures of dispersion: range – the difference between the largest and the smallest values of the sample R, standard deviation of the sample σ_x and coefficient of variation v_x,
- measures of asymmetry and concentration: skewness A_s and kurtosis k.

The statistical values of the measures of position, dispersion, asymmetry and concentration are presented in table 2 for the elastic modulus and in table 3 for the bending strength. The results of the statistical analysis are shown in the form of box plots in figures 6 and 7.

Next, on the basis of the statistical tests, the influence of the wood moisture on the elastic modulus and the bending strength has been estimated. For this purpose, the parametric test (unpaired Student's t-test) and nonparametric test (rank sum test) has been performed.

The unpaired Student's test is a parametric test based on estimates of the arithmetic average. The standard deviation of the normally distributed population from the samples has been drawn. The Mann-Whitney rank sum test (nonparametric type of test) is used when the samples are not drawn from normally distributed populations with the same variances. In order to select the appropriate test, it was necessary to examine whether the distribution is normal and perform a test for the equality of variances of two populations. The Shapiro-Wilk test has been performed to check the assumption about the normality of the distribution of the population. Then the equal variance test has been performed.

Table 2. Statistical description of elastic modulus for pine and fir wood

	Pine wood		Fir wood	
	Dry specimens	Wet specimens	Dry specimens	Wet specimens
	Measures of position			
$\bar{x}$ [GPa]	12.3	7.9	11.8	7.5
m_e [GPa]	12.4	7.9	11.6	7.5
	Measures of dispersion			
R [GPa]	4.2	3.0	4.8	1.9
σ_x [GPa]	1.6	1.3	2.1	0.8
v_x [%]	13.4	16.7	17.6	10.6
	Measures of asymmetry and concentration			
A_s [-]	-0.012	0.014	0.019	0.024
k [-]	-1.666	-2.494	-2.655	-2.260

Table 3. Statistical description of bending strength for pine and fir wood

	Pine wood		Fir wood	
	Dry specimens	Wet specimens	Dry specimens	Wet specimens
	Measures of position			
$\bar{x}$ [MPa]	71.9	39.6	63.2	36.6
m_e [MPa]	69.9	40.8	66.3	33.7
	Measures of dispersion			
R [MPa]	31.6	12.1	23.7	18.6
σ_x [MPa]	10.8	4.4	10.5	6.8
v_x [%]	15.1	11.2	16.6	18.5
	Measures of asymmetry and concentration			
A_s [-]	0.117	-0.127	-0.091	0.219
k [-]	0.795	-0.238	-2.058	1.244

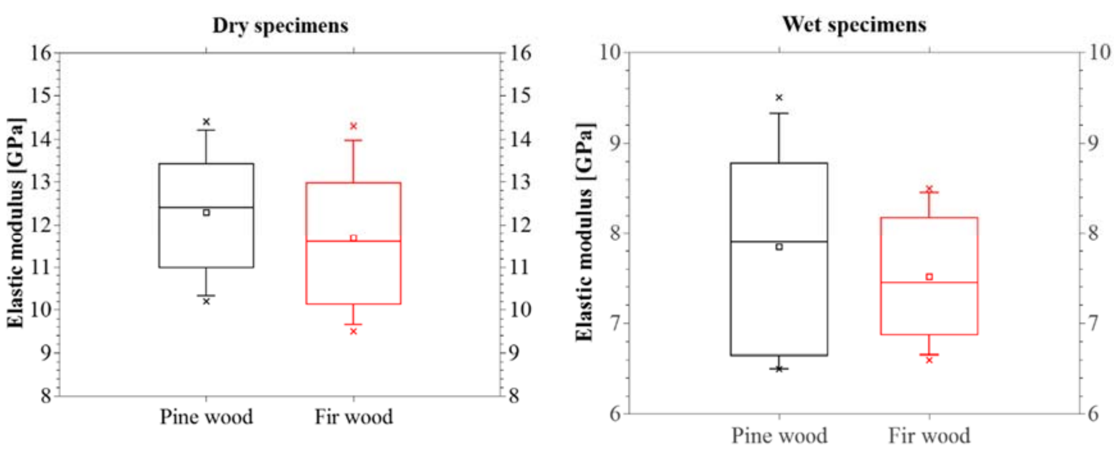

Figure 6. Analysis of elastic modulus for pine and fir wood

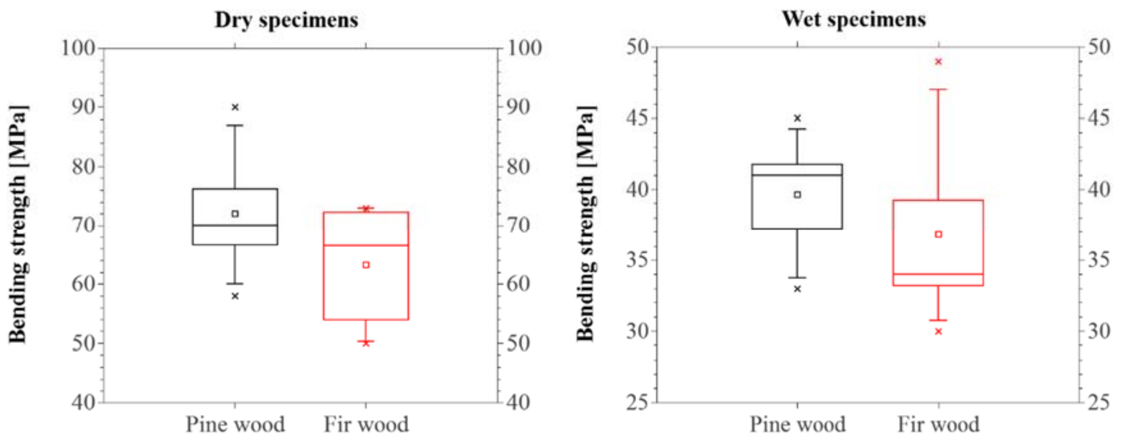

Figure 7. Analysis of bending strength for pine and fir wood

The influence of the wood moisture on the elastic modulus and the bending strength has been estimated for two group. It has been determined whether the moisture has a significant impact comparing:

- dry and wet specimens of the pine wood
- dry and wet specimens of the fir wood.

Tables 3 and 4, present information about the performed test for each group of population. The term "passed" means that the null hypothesis on the normality of the distribution cannot be rejected. In turn the term "failed" means that the null hypothesis should be rejected and the alternative hypothesis should be accepted. All statistical tests have been performed for the significance level $\alpha = 0.05$. The null hypothesis occurs, when it is assumed that there are no differences between the considered parameters of the two populations. The alternative hypothesis in both tests is assumed that there are differences between the considered parameters of two groups of population [12]. Depending on the results of the normality test and the equal variance test, the appropriate statistical tests have been performed.

The *p*-value has been calculated and is presented in tables 4 and 5. This index determines the highest level of significance at which the tested hypothesis is accepted. In the case of the normality test and equal variance test, there is no reason to reject the null hypothesis when $p \geq \alpha$ [13]. If $p < \alpha$ - the difference in the mean values of the two groups is greater than what would be expected by chance,–it is a statistically significant difference between the input groups. Such approach is used in the Student's test and the Mann-Whitney rank sum test.

Table 4. Statistical comparison of experimental data for obtained elastic modulus

	Dry and wet specimens of pine wood	*p*	Dry and wet specimens of fir wood	*p*
Normality test (Shapiro-Wilk)	passed	0.405	passed	0.922
Equal variance test	passed	0.564	failed	<0.050
Statistical test	Student's test	<0.050	Mann-Whitney rank sum test	<0.050

Table 5. Statistical comparison of experimental data for obtained bending strength

	Dry and wet specimens of pine wood	*p*	Dry and wet specimens of fir wood	*p*
Normality test (Shapiro-Wilk)	passed	0.793	passed	0.619
Equal variance test	passed	0.213	passed	0.238
Statistical test	Student's test	<0.050	Student's test	<0.050

5. Results and discussion

On the basis of the 4-point bending tests and statistical analysis, the influence of the wood moisture on the elastic modulus and the bending strength has been determined. The differences between dry and wet specimens of both species of the wood can be already be observed on the basis of the stress-stain functions (figures 4 and 5) without the calculated values of the elastic modulus and the bending strength. The calculated values of the elastic modulus and the bending strength presented in table 1 show that the wood moisture has an influence on the analysed mechanical properties. The percentage changes of the obtained average values of the elastic modulus and the bending strength between dry and wet specimens are presented in table 6.

Table 6. Percentage changes of the mechanical properties between dry and wet specimens

	Elastic modulus [GPa]	Bending strength [MPa]	Moisture [%]	Percentage change between elastic modulus [%]	Percentage change between bending strength [%]
Pine wood (dry specimens)	12.3	71.9	9.8	36	45
Pine wood (wet specimens)	7.9	39.6	21.4		
Fir wood (dry specimens)	11.8	63.2	10.8	36	42
Fir wood (wet specimens)	7.5	36.6	38.0		

On the basis of the data present in table 6, it has been noticed that the values of the bending strength of the wet specimens decreased by more than 40% in relation to the dry specimens, similar to what was reported in [14]. In turn, the values of the elastic modulus of the wet specimens has decreased by 36% in relation to dry specimens.

In order to check how big is the effect of the wood moisture on the values of the elastic modulus and the bending strength, the statistical tests have been performed. The results of the statistical test for the pine and fir wood and for both calculated mechanical properties are similar. The differences in the mean values of the two groups (wet and dry specimens) are greater than what would be expected by chance, so there is a statistically significant difference between the input groups.

6. Conclusions

Based on the performed laboratory tests and the results of the statistical analysis, it has been noted that the the wood moisture has a significant influence on the value of the elastic modulus of the wood and its bending strength. It has been noticed that the influence of the wood moisture is similar for both the elastic modulus and the bending strength for both species of the wood (pine and fir wood). The value of the elastic modulus has decreased by approximately 36% for both pine and fir wood. In turn, the value of the bending strength has decreased by more than 40% in relation to the moisture value of approximately 10%. These results show that the increase of the wood moisture causes the decrease of the mechanical properties.

The results of the statistical tests (Student's test and Mann-Whitney rank sum test) also confirm the effect of the wood moisture on the calculated mechanical properties. The differences in the mean values of the wet and dry specimens for both wood species are greater than expected by chance.

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