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EXPERIMENTAL AND NUMERICAL DETERMINATION OF THE LONGITUDINAL MODULUS OF ELASTICITY IN WOODEN STRUCTURES

This paper aims to experimentally and numerically determine the longitudinal modulus of elasticity by the four-point bending method. Samples of wooden beams over which the experimental research was performed were made of silver fir (Abies alba) as prescribed by standard EN 408. The experimental part includes determining bending strength and deformation forces. Experimentally determined bending strength and deflection forces were the input data for evaluating the modulus of elasticity of wooden beams. A numerical analysis of the bending strength by the finite element method was carried out using the ANSYS software package. The numerical model agreed well with the experiments in terms of bending. A numerical model can predict the bending of beams of different sizes. Results showed that the experimental and numerical values are close and usable for further exploitation. Comparison between the experimental and computational force versus the displacement response showed a very good correlation in the results for the fir wood specimens under four-point bending tests.

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Introduction

Wood is a natural, uniform and heterogeneous material whose properties significantly vary within and between different species. Wood is one of the earliest construction materials that has been used for millennia. The structural use of wood and wood-based composites continues to increase steadily. Even more, new wood-based materials continue to develop and are being successfully introduced into the engineering and construction marketplace [Kržišnik, et al. 2018; Kržišnik et al. 2020; Hasanagić et al. 2021]. Modern building practice would not be possible without the state of the art composites. Through consideration of its many benefits as a natural resource, wood is becoming progressively popular as a building material, not only for carpentry but also for constructing supporting structures [Bowyer et al. 2016]. This increased usage places wood, alone or as part of a composite [Clouston et al. 2005], in many novel applications where it has never been used before [Mahapatra and Gustavsson 2009].

Many studies have focused on determining material properties experimentally and numerically. Numerous contributing factors impact the mechanical properties of wood and wood products, such as wood species, tree growth velocity, density, and local singularities (knots, cracks, and slope of the grain). Important factors influencing the mechanical properties of wooden elements are knots and deviations of fibres.

Several researchers have developed finite element (FE) models to investigate the influence of knot and fibre deviations on wooden boards [Zandbergs and Smith 1988; Hackspiel et al. 2014; Lukacevic et al. 2014; Guindos and Guaita 2013]. Respective results describe experimental, analytical, genetic, and numerical modelling of wood and other wood-based materials, e.g., experimentally [Andor, et al. 2015; Raftery and Kelly 2015], analytical [Hasanagić et al. 2020; Winter, et al. 2012; Thorhallsson, et.al 2017; Nadir et al. 2016], genetic [Hasanagić 2018; Chu, et al. 2022; Hasanagić 2022] and numerically [Valipour and Crews 2011; Raftery and Harte 2013; de Jesus et. Al 2012; Rescalvo et al. 2020].

For example, the researchers [Hu and Guan 2019; Fajdiga et al. 2019] experimentally evaluated the elastic properties of beech and spruce wood using the finite element method (FEM). Respective authors compared the experimental and computational force and displacement response. This approach showed an excellent correlation in the results for the wood specimens under three-point bending tests, with Pearson′s correlation coefficient of $r = 0.994$ for the tangential and $r = 0.988$ for the radial orientation. The authors [Fajdiga et al. 2016] dealt with heat-treated beech wood, where it is experimental and numerical procedures were used to investigate the impact of heat treatment processes on the behaviour of wood without defects under compressive loads. In the research [Daudeville 1999], the fracture of a wooden structure was analysed, and the model of damage mechanics for the simulation of fracture in wood using experimental and numerical procedures was presented. Stresses and deformations of different thicknesses of softwood and hardwood during bending at three points were investigated using the finite element method [Gaff et al. 2015].

This study attempts to experimentally and numerically evaluate the longitudinal modulus of elasticity by the four-point bending method. The experimental part includes determining bending strength and deformation for wooden beams of fir trees. Experimentally determined bending and deflection forces values will be the input data for determining the modulus of elasticity of wooden beams. In addition to the experimental part, a numerical analysis by the finite element method will be performed, which will provide inputs for the numerical modelling of the modulus of elasticity. This study should be able to identify the influence of some selected parameters such as material properties, thickness, width, and length. Numerical simulation was performed to try to predict the change in bending behaviour of solid fir beams, where the model can be seen matching when it comes to the shift of experimentally tested samples and numerical simulation.

Materials and methods

Experimental test program

The experimental test series used samples of silver fir wood (*Abies alba*) from Bosnia and Herzegovina for bending, whose average density and moisture content were 0.43 g/cm^3, and 10%, respectively. The density obtained based on ISO-3131:2016 standard. All samples were weighed using an electronic balance with an accuracy of 0.01 g to note their masses, whereas their dimensions for volume determination were measured with an electronic vernier calliper with an accuracy of 0.1 mm as specified in ISO 3131. Density was then determined as: Density=mass/volume. The moisture (MC) contents of samples were measured using a moisture meter (Nigos DVD 240) with an accuracy of ±2 %. Samples were kept in a constant climate room for with 20 °C temperature and 65% relative humidity to reach 12% equilibrium moisture content. We started with an assortment of 30 samples prepared according to their suitability for our needs according to standard EN 408:2013. Based on similar density, we further eliminated the samples until we obtained a series of 5 samples (Figure 2), for which the wood density between extremes does not deviate more than approx.

10%.The bending process was performed on rectangular four-point bending fir wood samples (Figure 1) with dimensions shown in Table 1:

Table 1. Dimensions of fir samples

Sample dimensions	Fir 1	Fir 2	Fir 3	Fir 4	Fir 5
b (mm)	49.20	49.60	49.70	49.40	49.60
h (mm)	20.60	20.70	20.50	20.50	20.70
l (mm)	380.00	380.0	380.00	380.00	380.00

During the preparation of the samples, special attention was paid to achieving the best parallel orientation of the wood fibres and the growth rings along the entire length of the sample. Samples were also visually inspected and sorted according to the ring-width and orientation.

Bending and tensile testing procedures

Solid wood for various construction applications must be sorted by its strength before use. To make the process as feasible as possible, the measurement usually focuses on the most important mechanical properties: density, modulus of elasticity (MOE), and bending strength, according to standard [EN 408:2013]. The tests of the module of elastic, maximal force, and max displacement on the bending of five samples of fir wood were performed. The samples were always positioned so that they were subjected to maximum load to the limit of elasticity. The test samples, having a minimum length of approximately 19 times the depth of the section, were supported and symmetrically loaded in bending at two points throughout approximately 18 times the depth. The maximum force was measured within the loading points shown in Figure 1. From the measured parameters of the above tests, the MOE a may be calculated using the following equation (1) [EN 408 2013]:

$$MOE = \frac{a \cdot l_1^2 (F_2 - F_1)}{16 \cdot I \ (w_2 - w_1)} \ [\text{N/mm}^2] \tag{1}$$

where:
F_2,F_1= load in newtons on the regression line with a correlation coefficient of 0.99
w_2,w_1 =(increment of deformation in millimeters corresponding to F_2-F_1) [mm].
a = distance between a loading position and the nearest support in a bending test in millimeters [mm]
I = second moments of area, in millimetres to the fourth power [mm]
l_1 = gauge length for the determination of modulus of elasticity in millimetres [mm].

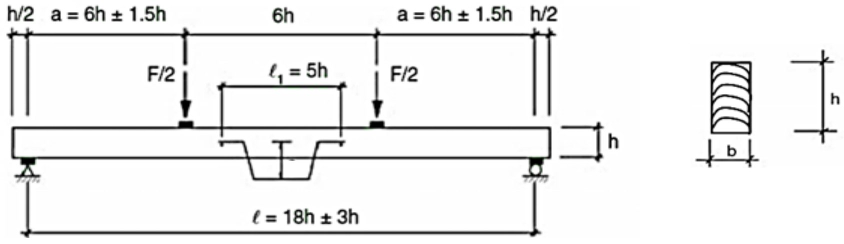


Fig. 1. Schematic illustration of the four-point bending test arrangement [EN 408: 2013]

The experiments used testing machine type SIL-50KNAG, manufactured by SHIMADZU, in which a working cylinder is located in the upper part of the testing machine. The working cylinder moves down (bending), while the lower head is stationary. Then, through a computer connected to the SIL-50KNAG type testing machine, the bending is measured at four points so that the values of the force achieved can be read in the diagram.

The sample is placed between the heads, after which the MOE, displacement, and intensity of the bending force are examined. This procedure tests the mechanical properties of a material and characterises the mechanical resistance of the material and its deformability. The test speed is set on the computer to 1 mm/min. So, taking into account the preparatory - final time and extension time, the duration of each experiment is about 10 minutes.

Numerical analysis

Fir-wood beams were modelled in the ANSYS-2021R2 computer program by specifying material characteristics and girder geometry. The performed analysis is geometrically nonlinear, and a static calculation was performed. The ANSYS computer program uses Newton-Raphson method [Akram and Ann 2015] as an iterative solution procedure. In each iterative step, the tangential stiffness matrix changes, representing the slope of the curve in the deflection diagram of the ground state from which the iterative step starts. The deflection increment was calculated at each step until the force imbalance (residual) decreased to a satisfactorily small value. A coordinate system consisting of tangential (x), longitudinal (y), and radial components (z) was used in the modelling. The selected finite element mesh size is 15 mm, the number of nodes is 937, and the number of finite elements is 410 (Table 2). Deformations, displacements and stresses were observed in the computer model.

Table 2. Wooden beam geometry and finite element mesh characteristics

Details of Solid		Details of Mesh	
Suppressed	No	Display Style	Use Geometry Setting
ID (Beta)	19	Physics Preference	Mechanical
Stiffness Behavior	Flexibile	Element Order	Quadratic
Coordinate System	Default	Element Size	15.0 mm
Reference Tem.	By Environment	**Advanced**	
Treatment	None	Number CPU	Program Controlled
Material		Straight Side Element	No
Assignment	Solid Wood	Rigid Body	Dimensionally Reduced
Nonlinear Effects	No	Triangle Surface	Program Controlled
Theral Strain Effects	No	Use Asymmetrics	No
Bounding Box		Topology Checking	Yes
Length X	360 mm	Pinch Tolerance	Please Define
Length Y	20.6 mm	Generate Pinch	No
Length	49.5 mm	**Statistics**	
		Nodes	937
		Elements	410

Results and discussion

The paper presents the results of the study of experimental research and numerical modelling of the significant factors: length (l), width (b), and thickness (h) of the workpiece of the solid wood.

For this research on the basis of similar density, we eliminated the samples and a series of 5 samples was determined, for which the wood density between the extremes did not deviate by more than approx. 10%. Out of a total of five selected samples were tested flexurally until rupture. The results are presented in Table 4.

Table 3. Experimental results

Sample Nr.	Density Densiti (ρ) [g/cm^3]	MC (%)	Force [N]	MOE [N/mm^2]
1	0.50	10.0	3051	15185
2	0.49	9.1	2855	13478
3	0.48	9.1	3042	13500
4	0.53	11.2	3199	11360
5	0.37	11.5	3343	14236
6	0.55	10.7	2635	12897
7	0.43	8.6	2929	13181
8	0.48	11.1	3021	13463
9	0.44	11.0	3143	13098
10	0.52	10.9	2456	12895
11	0.48	10.0	3834	13798
12	0.35	9.6	4341	15539
13	0.40	9.6	1489	10879
14	0.51	9.9	2285	11902
15	0.57	9.3	4036	14296
16	0.50	11.8	2431	12689
17	0.53	11.0	2960	12891
18	0.46	9.1	3556	13895
19	0.47	8.7	2417	10391
20	0.41	8.8	3243	13061
21	0.57	10.4	2475	12780
22	0.50	9.7	2234	12542
23	0,41	8.9	2521	11269
24	0.49	9.7	2685	12490
25	0.34	10.0	2098	11871
26	0.46	9.0	2142	11784
27	0.44	8.8	2245	10776
28	0.48	9.2	2630	12064
29	0.50	8.2	2511	12086
30	0.5	8.7	2642	13724
Stdev.	0.058	0.98	610.8	1234.4
Avg.	0.472	9.7	2814.9	12800.6
Max	0.57	11.8	4341	15539
Min	0.34	8.2	1489	10391

The experiment results and numerical simulation represent the intensity of MOE and force to the critical bending point (Table 4). The results obtained by numerical modelling in ANSYS (Fig. 3) and experimental test (Fig. 2) and a good match of the results can be observed.

Table 4. Results of experimental and numerical test

Samples Nr.	Mass (m) [g]	Density (ρ) [g/cm^3]	Force F [N]	MOE (E) [N/mm^2]	MOE (N) [N/mm^2]	MOE (%)	Maximal disp. (E) (d) [mm]	Maximal disp.(N) (d) [mm]	Maximal disp. (%)
Fir 7	25.11	0.43	2929	13181	11108	18.66	-7.62	-7.16	6.42
Fir 13	23.43	0.40	1489	10879	10839	0.37	-4.86	-5.14	5.45
Fir 19	24.49	0.47	2417	10391	10007	3.84	-7.22	-8.54	15.46
Fir 23	25,01	0.41	2521	11269	11242	0.24	-7.95	-7.51	5.86
Fir 27	25.76	0.44	2245	10776	9881	9.06	-7.42	-7.36	0.82
Average	24.76	0.43	2320	11299	10786	4.76	-7.01	-7.14	1.76
Maximum	25.76	0.47	2929	13181	11242	17.25	-7.95	-8.54	6.91
Minimum	23.43	0.40	1489	10391	10007	3.84	-4.86	-5.14	5.45

of elasticity stretch in proportion to the load. The elongation displacement will increase proportionally for a particular increase in force F. The test tube is moved according to Hooke's law. All deformations of the material in this area are elastic.

After the cessation of the load, the test tube returns to the initial position. To calculate a mean response force-displacement curve for each specimen's orientation, data from all five individual experimental tests were used for averaging (Figure 2).

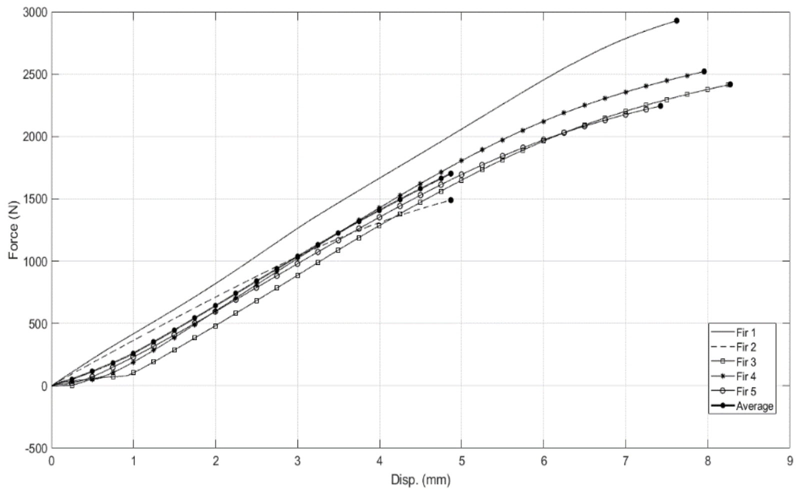


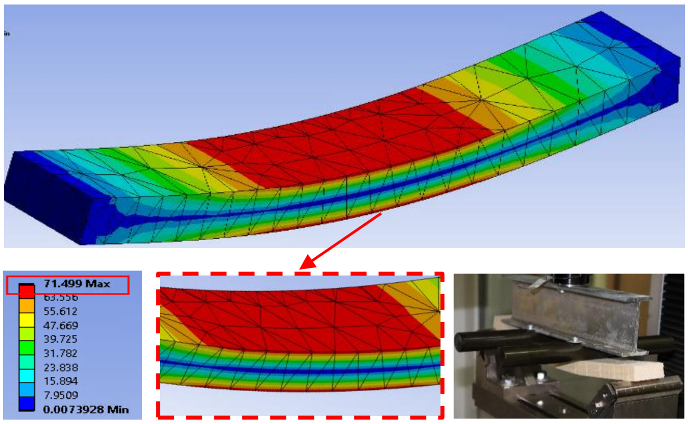
Fig. 2. Experimental results of the applied force and maximum deflection

The model for numerical analysis of the flexural strength of specimens is designed to describe as accurately as possible boundary conditions and loads from an experiment on a physical model.

The model shown in Figure 3 consists of simple sample geometry, supported by two supports and two indentations in the upper part that bend the sample (beam) on the y-axis. The numerical model was generated using finite element method elements as a required material model.

One reason for this is to define the direction of the fibres in wood. Following the conditions of the experimental determination of flexural strength, the supports of the model are clamped.

Due to the force acting on the beam, there would be no translation of the elements and displacement of the supports. The bending simulation of the test tube for the type of fir is shown in Figures 3 and 4.



a) b)

Fig. 3. Comparison between bending modes of the fir wood: a) numerical b) experimental

Local stress concentration due to load distribution at the end of the samples is represented in a numerical model (red). Figure 3 shows the stress distribution is parallel to the grain for the same fir pattern profile. Graphic representations of stress show concentrations as stresses at bending at four points.

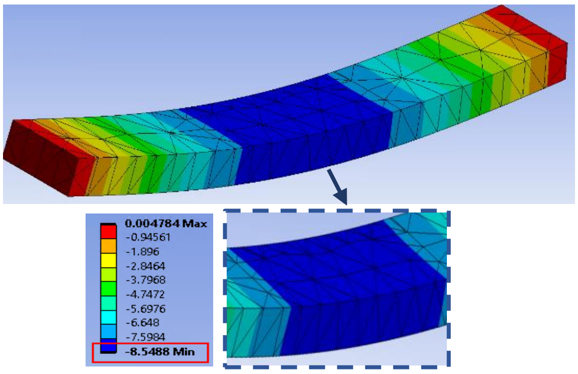


Fig. 4. Graphical representation of the numerical results of deflection displacement model representation

The numerical displacement of the mean bending range was calculated. The projected numerical shift was slightly more significant was -8.54 mm, slightly higher (a difference of 16%, Figure 4) than the mean experimental value of -7.22 mm.

Conclusion

The computational model using finite element method was created and validated based on the experimental results by comparing mechanical responses. The computational model was validated using the inverse procedure to determine the constitutive material parameters. Five four-point bending tests were carried out to achieve a representative sample of experimental tests. Numerical simulations have shown the possibility of analysing the evolution of displacement in the considered wooden beams. The numerical model has been validated by comparing computational and experimental results, where the force-displacement diagrams were compared. The comparison showed a very good correlation of the results, with Pearson's correlation coefficient of r = 0.995. However, clean specimens and a homogeneous material model were considered, a first attempt to create a numerical model for later bending.

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