BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iaşi
Tomul LVIII (LXII), Fasc. 1, 2012
Secţia
CONSTRUCŢII. ARHITECTURĂ

ANALYSIS OF WOOD BENDING PROPERTIES ON STANDARDIZED SAMPLES AND STRUCTURAL SIZE BEAMS TESTS

BY

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Received: January 11, 2012
Accepted for publication: Febuary 23, 2012

Abstract. Wood has several unique, independent mechanical properties. Physical and mechanical properties of wood have a large number of values determined by the influences of an extended number of factors. These timber properties do vary from species to species and even within species due to environmental conditions during growth. However, because of its cellular structure and the way in which these cells are organized the strength of the wood product depends mainly on the direction of any loading. This paper presents an analysis of the results obtained by testing standardized specimens and structural size beams, according to standards requirements in force for simple bending. Small samples were tested for three-point bending and real scale beams were tested for four-point bending. Conclusions are based on the obtained results.

Key words: wood elements; bending; laboratory test.

1. Introduction

Since ancient times, wood and stone have been important building materials. Wood is an inexpensive material. Forest is a wood factory which produces wood using only solar energy. Only minimum amounts of power are

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required for maintaining the forest, tree-conversion and wood products transportation. In processing and production too, wood requires far less energy than other building materials.

This concept of environmental performance becomes clearer when wood is compared with steel and concrete when there are distinct differences between them in terms of their environmental impacts. Recent research studies confirmed that houses made from wood present significantly lower risks for the environment. Wood-based building materials require less energy to be produced, emit less pollution to the air and water, contribute with lower amounts of CO_2 to the atmosphere, are easily disposed of or recycled, and are derived from a renewable resource. It can be easily concluded that the environmental advantages of wood with regard to steel and concrete are obvious. Life-cycle analysis results for the steel-framed *vs*. wood-framed home showed that the steel-framed home used 17% more energy; had 26% more global warming potential; had 14% more air emissions; had over 300% more water emissions and had about the same level of solid waste production. Analysis results for the concrete- *vs*. wood-framed home showed that the concrete-framed home used 16% more energy; had 31% more global warming potential; had 23% more air emissions; had roughly the same level of water emissions and produced 51% more solid waste.

Wood is an anisotropic material, usually considered an orthotropic material, due to the wood fiber orientation, and due to the way in which a tree diameter increases in the period of growth. Therefore, the wood physical and mechanical properties vary in relation to three mutually perpendicular axes: longitudinal, radial and tangential axis.

Longitudinal axis is the axis parallel to fiber, radial axis is perpendicular to the fiber direction and normal to the growth rings and the tangential axis is perpendicular to the fiber direction and tangent to the growth rings.

In terms of value, most properties of wood vary in each of these three directions, differences between the same properties along the radial and tangential axes are relatively minor compared to the same property differences of the radial or tangential axis and longitudinal axis (Isopescu, 2002; Decher, 2003). Therefore, generally in design, are counted two categories of properties assessed: in the longitudinal direction and in the transverse direction (Fig. 1).

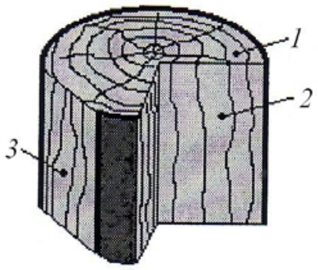

Fig. 1 – Principal sections in timber: *1* – transverse section (*T*), *2* – radial section (*R*), *3* – longitudinal section (*L*).

Wood structures have traditionally been analysed based on simple calculation assumptions validated by extensive experimental tests. Strength capability of wood elements is difficult to assess because the strength of wood is a function of several parameters including the moisture content, density, and duration of the applied load, size of members and presence of various strength-reducing characteristics such as slope of grain, knots, fissures and wane. To overcome this difficulty, the stress grading method of strength classification has been developed and currently numerical simulations based on finite element method (FEM) are considered design procedures for wood frame buildings (Furdui, 2005).

2. Experimental Data

The wood beams were analysed by laboratory tests performed at the Faculty of Civil Engineering and Building Services of "Gheorghe Asachi" Technical University of Iaşi. The wood used to create specimens is of softwood species, namely spruce. Both small and large specimens were manufactured to achieve the conditions imposed by the standards for determining wood behaviour to static bending tests, ASTM D 143-09 *Test Methods for Small Clear Specimens of Timber,* ASTM D 198-09 *Test Methods of Static Tests of Lumber in Structural Sizes* and SR EN 408:2004: *Structuri de lemn. Lemn masiv şi lemn lamelat încleiat. Determinarea anumitor proprietăţi fizice şi mecanice*.

Before tests, the wood elements were checked to determine the nominal value of their real dimension. The moisture content for each specimen has been measured. To verify the laboratory conditions, humidity and air temperature have been measured in the room where the tests were conducted, having the values of 60% and 21°C, respectively.

The following are the results of laboratory tests performed on specific wood specimens subjected to static bending.

2.1. Static Three-Point Bending Test of Wood Specimens

To determine the static bending (flexural) strength of wood, laboratory tests were carried out according to SR ISO 3133:2008 and ASTM 04.10 Wood D143-09. The working procedure and the achievement of expressing quality of specimens have complied with these the standards (SR ISO 3133, 2008).

Experimental tests were made using the equipment Zwick / Roell Material Testing Machine BP1-F1000SN.M11. According to the standard, a total of 10 specimens was considered, having the dimensions of 20 mm × 20 mm in cross-section ($b \times h$) and 380 mm length (Fig. 2).

Specimens were simply supported, the distance (L) between supports was of 240 mm, and the load was applied midway (the mid-span of 240 mm – Fig. 3), on the radial surfaces. The load was applied continuously with constant test speed of 0.85 MPa/s, providing a break for specimens in 102 s (about 1.7 min) (Budescu *et al.*, 1982).

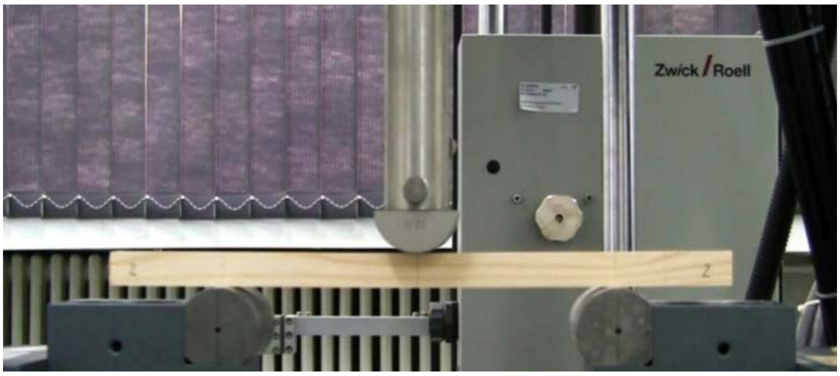

Fig. 2 – Test equipment and arrangements for static bending test.

Following the static bending (flexural) test (Fig. 3), the results shown in Table 1 were obtained. The corrections of the results to moisture content (MC) of 12% are presented in Table 2.

Table 1
Static Bending (Flexural) Test Data on Small Specimens

Specimen number	ρ_{rel} g/m^3	W %	$P_{\max}$ N	$\delta_{\max}$ mm	S mm	$\delta_{\max,\mathrm{real}}$ mm	σ_{bW} MPa	E_L MPa
1	472.16	7.4	1,730	7.5	0.30	7.20	74.54	7,120
2	478.64	7.4	2,090	6.5	0.30	6.20	83.84	8,200
3	502.02	8.0	1,830	5.8	0.25	5.55	74.11	7,130
4	490.39	7.0	2,030	6.1	0.30	5.80	80.94	8,850
5	508.48	7.2	2,120	5.9	0.15	5.75	88.74	9,200
6	521.10	7.6	2,340	7.3	0.20	7.10	95.91	10,300
7	498.11	7.2	2,000	6.3	0.35	5.95	85.89	8,840
8	524.76	7.0	2,430	7.3	0.35	6.95	93.26	9,400
9	487.16	7.4	1,880	5.9	0.35	5.55	76.93	7,800
10	502.04	7.8	1,960	6.4	0.15	6.25	80.76	7,510
Mean value	498.50	7.4	2,041	6.5	0.27	6.23	83.49	8,435

Data from Tables 1 and 2 represents: ρ_{rel} – relative density of specimens, [g/m^3]; W – specimens moisture content according to ISO SR EN 13183-1, [g/m^3] (SR EN 13183-1, 2003); $P_{\max}$ – failure load, [N]; $\delta_{\max}$ – apparent deflection at failure, [mm]; S – total crushing, taking into account local crushing of the load application and the bearing areas, [mm]; $\delta_{\max,\ \mathrm{real}}$ – failure deflection, also considering local crushing, [mm]; E_L – elasticity modulus, [MPa]; σ_{bW} – static bending strength for W moisture content during the test, calculated with the relation

$$\sigma_{bW} = \frac{M_{z,\max}}{W_z} = \frac{P_{\max} L/2}{bh^2/6} = \frac{3P_{\max}}{2bh^2}, \tag{1}$$

Table 2

Modified Static Bending (Flexural) Test Data to 12% MC

Specimen number	W %	σ_{bW} MPa	σ_{b12} MPa	E_L MPa	E_{L12} MPa
1	7.4	74.54	111.95	7,120	7,596.47
2	7.4	83.84	127.26	8,200	8,748.74
3	8.0	74.11	103.89	7,130	7,544.90
4	7.0	80.94	128.78	8,850	9,493.74
5	7.2	88.74	138.75	9,200	9,842.43
6	7.6	95.91	143.56	10,300	10,959.30
7	7.2	85.89	133.92	8,840	9,457.29
8	7.0	93.26	150.26	9,400	10,083.74
9	7.4	76.93	115.88	7,800	8,321.97
10	7.8	80.76	116.57	7,510	7,968.87
Mean value	7.4	83.49	127.08	8,435	9,003.46

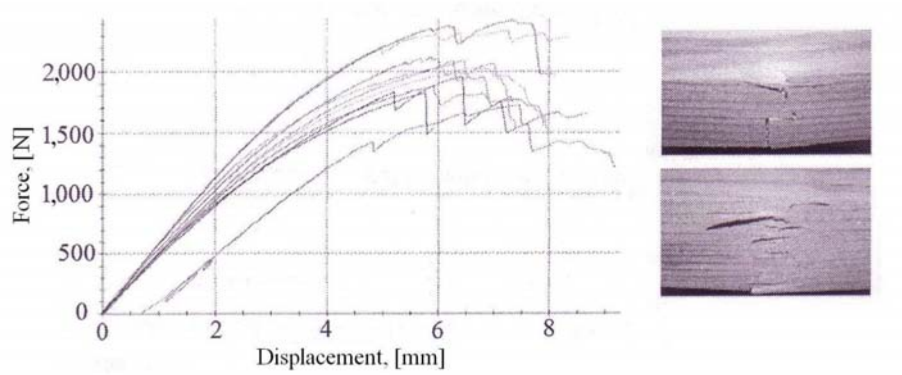

Fig. 3 – Static bending test: force *vs*. displacement graph and failure modes of wood specimens.

σ_{b12}, [MPa], is the static bending strength for moisture content of 12%, determined by the relationship

$$\sigma_{b12} = \sigma_{bW} + \frac{\sigma_{bW} - 16.6}{0.276 - W}(W - 12), \tag{2}$$

E_{L12}, [MPa] – elasticity modulus for moisture content of 12%, determined by the relationship

$$E_{L12} = E_L \frac{1,857 - 0.0237W}{1,857 - 0.0237 \times 12}. \tag{3}$$

The mean elasticity modulus for the three-bending test reached a value of 9,003.46 MPa.

2.2. Static Four-Point Bending Test of Wood Beams

The four-point bending test of wood was developed according to ASTM 04.10 Wood D143-09 and SR EN 408:2004. More accurately speaking, the beams were subjected to third-point loading, which is a special case of four-point bending where the two loads were placed at a distance $a = L/3$ from the supports, where L is the beam span (ASTM 04.10, 2004; Eurocode EC5, 1995).

Experimental tests were made on the Universal Hydraulic Press WAW-600E (Fig. 4) and the deflection at mid span was determined by means of an ”Epsilon Technology Corp” transducer attached to the beam at the neutral axis level.

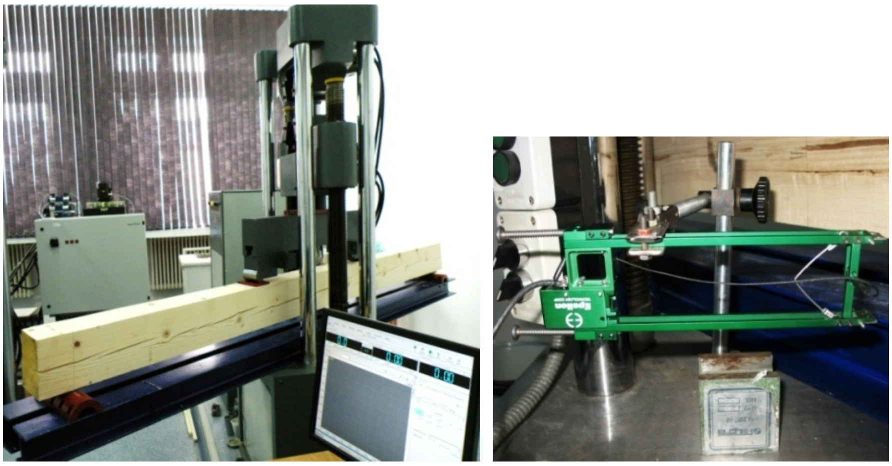

Fig. 4 – Test equipment and arrangements for the four-point bending test.

Structural size beam have a rectangular shape with the cross-sectional dimensions of 100 mm × 160 mm ($b \times h$), and 2,600 mm length. The span of the beams was selected to be of 2,400 mm.

The load was applied in two points, placed symmetrically on the beam, at a = 800 mm distance from the supports faces.

Tests were performed with a number of 9 structural size beams (Fig. 5). Constant speed of load application was imposed to 0.100 kN/s. The obtained results are presented in Table 3, with: t, [s] – test duration; δ, [mm] – apparent deflection at time $t \approx 300$ s; P, [N] – load at $t \approx 300$ s; E_L, [MPa] – elasticity modulus for moisture content of W%, determined with relation (ASTM 04.10, 2004)

$$E_L = \frac{23PL^3}{108bh^3\Delta}, \tag{4}$$

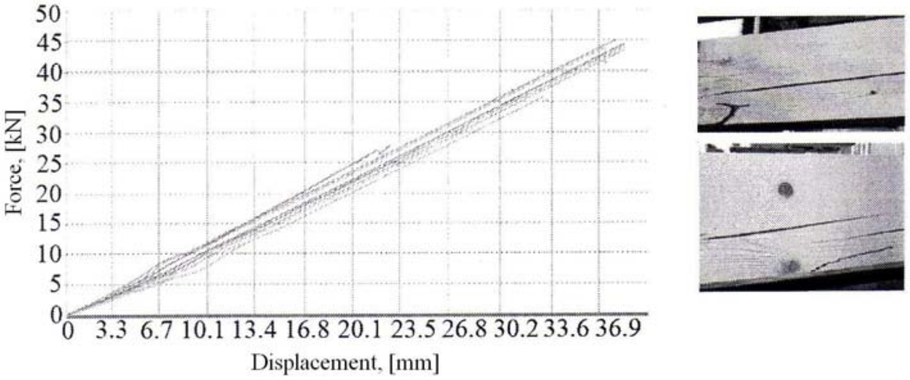

Fig. 5 – Static bending test: force *vs.* displacement graph and failure modes of wood beams.

Table 3

Static Bending (Flexural) Test Data on Structural Size Beams

Beam number	t s	δ mm	P N	E_L MPa	E_{L12} MPa
1	286	24.31	27,430	8,109.96	8,525.51
2	261	23.55	22,890	6,986.07	7,407.20
3	306	23.20	28,950	8,968.88	9,509.55
4	300	20.64	30,810	10,729.01	11,311.11
5	300	20.69	30,700	10,664.87	11,275.63
6	300	23.05	30,000	9,354.66	10,031.37
7	301	24.50	30,530	8,956.50	9,658.40
8	301	24.35	27,500	8,117.30	8,680.03
9	321	32.06	30,600	6,860.18	7,356.44
Mean value	297.33	24.04	28,823	8,749.72	9,306.14

where Δ, [mm], is the full-span deflection according to the load P, measured at the neutral axis level, at mid-span of the beam of length L; E_{L12}, [MPa] –

elasticity modulus for moisture content of 12%, determined by the formula given in Wood Handbook (2010)

$$E_{L12} = E_L \frac{1{,}857 - 0.0237W}{1{,}857 - 0.0237 \times 12}. \qquad (5)$$

Therefore, the mean elasticity modulus for the four-bending test has the value of 9,306.14 MPa.

3. Evaluation of the Strength Class for the Analysed Wood Elements

The characteristic density, average elasticity modulus and bending strength values with humidity adjustments, presented in Tables 1,...,3, have been corrected by statistical analysis and are presented in Table 4.

Table 4
Statistical Correction for Wood Specimens

Characteristic value, x_i	Average value $\overline{x_i}$	Standard deviation x_i $s_m = \pm\sqrt{\frac{\sum_{i=1}^{n=10}\left(x_i - \overline{x_i}\right)^2}{n(n-1)}}$	Real value $\overline{x_i} + s_m$
Flexural strength of small specimens, [MPa]			
Table 2 for $\sigma_{b12} = x_i$	127	4.71	132
Elasticity modulus of small specimens, [MPa]			
Table 2 for $E_{12} = x_i$	9,003	362.11	9,365.11
Characteristic density of small specimens, [kg/m^3]			
Table 1 for $\rho_{\text{rel}} = x_i$	498.50	–16.16	482.34
Elasticity modulus of structural size beams, [MPa]			
Table 3 for $E_{L12} = x_i$	9,306.14	485.89	9,792.04

The tabulated values (standardized) were based on the estimated average property values obtained on all wood specimens. The characteristic value was obtained as the product of the average values of property due to the wood test specimens and the average coefficient of variation for the property.

Average coefficients of variation for the mechanical properties are a statistical estimate of the influences identified by testing in laboratory conditions, caused by the variability of sizes, by those defects invisible in a natural element and by the environmental conditions in which the tree grew. The average coefficients of variation require a large number of results obtained in laboratory tests. In the paper “Wood Handbook, Wood as an Engineering Material” (2010), the average values for the coefficients of variation, p_k , are presented. These coefficients were obtained by statistical mediation of results existing in the technical literature for wood products, worldwide. The value of the average coefficient of variation for characteristic bending strength evaluation is $p_k = 16\%$.

Determination of strength class to group of wooden beams used to create specimens for laboratory testing is based on the result for the modulus of elasticity.

According to the corrections in Table 4, the elasticity modulus is $E =$ $= 9,365.114$ ... $9,792.037$ MPa, therefore the strength class for the analysed wood is considered to be C18.

The characteristic bending strength is now evaluated using the average coefficients of variation

$$f_{m,k} = \sigma_{b12} p_k = 21.12 \text{ MPa}. \tag{6}$$

European norm DIN EN 384-2004 shows that all the important characteristic strength and stiffness properties can be approximated from either bending strength, modulus of elasticity or density (DIN EN 384-2004). The values obtained in this manner are presented in Table 5 and compared to the values given by SR EN 338, 1997 for wood of strength class C18.

Table 5

Values of Properties for C18

Property	Values for C18	Evaluation procedures	Experimental test results
Characteristic bending strength, [MPa]	18	$f_{m,k}$ in Table 4	21.12
Characteristic tensile strength parallel to the grain, [MPa]	11	$f_{t,0,k} = 0.60 f_{m,k}$	12.67
Characteristic tensile strength perpendicular to the grain, [MPa]	0.3	$f_{t,90,k} = 0.0015 \rho_k$	0.48
Characteristic compression strength parallel to the grain, [MPa]	18	$f_{c,0,k} = 5 f_{m,k}^{0.45}$	19.73
Characteristic compression strength perpendicular to the grain, [MPa]	4.8	$f_{t,90,k} = 0.007 \rho_k$	3.38
Characteristic shear strength, [MPa]	2.0	$f_{v,k} = 0.2 f_{m,k}^{0.8}$	2.13
Elasticity modulus parallel to the grain, [MPa]	9,000	$E_{0,\text{mean}}$ in Table 4	9,365.11
Elasticity modulus to 5%, [MPa]	6,000	$E_{0.05} = 0.67 E_{0,\text{mean}}$	6,324.03
Elasticity modulus perpendicular to the grain, [MPa]	300	$E_{90,\text{mean}} = E_{0,\text{mean}}/30$	314.63
Shear elasticity modulus, [MPa]	560	$G_{\text{mean}} = E_{0,\text{mean}}$	589.93
Characteristic density, [kg/m^3]	320	ρ_k in Table 4	482.34

5. Conclusions

The need for a standardized procedure for assigning working stresses to wood elements was recognized in the early 1900's. At that time, there was considerable debate on how to test wood for mechanical properties. One side advocated testing small clear specimens, and the other promoted tests of structural-size material. The "small clear" side won out.

Complete investigation of wood properties is available for consideration in a broad sense in relation to its usage. A points score, both for and against, can be made for most wood elements provided that the user is able to agree upon the properties which are essential.

Values for mechanical properties obtained in standard laboratory tests should be adjusted by the mathematical models and the average coefficients of variation to reach the characteristic values set in the standards, norms and design codes. These adjustments take into account uncertainties arising from the differences between laboratory specimens of wood and wooden building elements of full scale.

Wood density and bending strength have a close affinity with a number of other properties which have great significance in successful timber utilization.

Both tests, on specimens or structural size beams, have shown that if the wood came from the same batch, the results fall into a population of values confirmed by the tabulated values which are given in codes. However, almost all results have differences that do not fit the tabulated values perfectly. In nearly all cases where there is not a good match with, the tabulated design property values are used.

For structural purposes the wood elements should be supplied in 'strength classes' that determine the allowable working stresses. As the strength class depends on both the species and the grade of the piece, design engineers may specify the required strength class of the timber, leaving it to the supplier to select a species and grade to meet that specification.

Acknowledgement. This paper was realized with the support of EURODOC "Doctoral Scholarships for Research Performance at European Level" project, financed by the European Social Found and Romanian Government.

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ANALIZA PROPRIETĂŢILOR LEMNULUI PE EPRUVETE STANDARD ŞI PE GRINZI LA SCARĂ NATURALĂ SUPUSE LA ÎNCOVOIERE

(Rezumat)

Lemnul are proprietăţi mecanice unice şi independente. Proprietăţile fizice şi mecanice ale lemnului au o variabilitate mare, fiind influenţate de un număr ridicat de factori. Aceste proprietăţi ale lemnului variază de la o specie la alta şi chiar în cadrul aceleaşi specii, datorită condiţiilor de mediu din timpul creşterii. Totuşi, datorită structurii celulare şi a modului în care celulele sunt distribuite, rezistenţa produselor din lemn este dependentă în special de direcţia de solicitare. Studiul efectuat prezintă analiza rezultatelor obţinute în urma testării unor epruvete standard şi a unor grinzi la scară naturală, respectând cerinţele din standardele în vigoare pentru încovoiere statică. Epruvetele de mici dimensiuni au fost testate la încovoiere în trei puncte iar grinzile de mărime naturală au fost testate la încovoiere în patru puncte. În final au fost formulate concluzii bazate pe rezultatele obţinute.