ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 11, No. 1. 2005

Compression Strength of Oak and Ash Wood Perpendicular to Grain

Inga JUODEIKIENĖ*, **Valdas NORVYDAS**

Department of Mechanical Wood Technology, Kaunas University of Technology, Studentų 56, LT-51424 Kaunas, Lithuania

Received 01 September 2004; accepted 30 December 2004

The strength of oak and ash wood was studied by compressing it perpendicular to grain in radial and tangential directions. The dependence of the strength on the number of annual rings in sample cross-section was analyzed. Experiments were carried out with oak and ash wood samples, the cross-section of which contained from 4 to 14 annual rings. Mean conventional density of oak wood is 613 kg/m^3 that of ash wood is 555 kg/m^3. It was found that the strength of compressed oak wood of the mentioned density in radial direction comprises 21.45 MPa, in tangential is 9.43 MPa, while that of ash wood in radial direction is 10.73 MPa in tangential is 15.25 MPa. Compressed oak wood perpendicular to grain in both directions, while ash wood in radial direction, the strength decreases with increasing number of annual rings in sample cross-section, i.e. when annual rings become narrower.

Keywords: oak wood, ash wood, compressing perpendicular to grain, annual rings.

INTRODUCTION

Wood is one of the most widely used materials not only in wood processing industry, but also in other fields of industry (construction, chemistry, machinery etc.) [1, 2]. Wood as material is very advantageous: it is easily processed (compared to metals and stone), is strength resistant, is hardly affected by acids and alkali, has low heat conductivity, is characterized by good adhesion properties, pleasant appearance and good finishing [3, 4]. However, it has some negative features: under changing moisture content wood swells or shrinks, its strength, hardness and other mechanical properties differ in different directions, usually wood has defects which worsen the quality of wood and its products [5, 6]. Therefore, to use this material properly and efficiently, it is necessary to know its physical and mechanical properties.

One of the most characteristic and more usually applied wood loading types is compression. Compression can be performed perpendicular or parallel to grain using three loading modes (Fig. 1):

a) loading is applied trough the all surface area of sample (pressing);

b) loading affects only some part of sample surface area, i.e. only the part of the length, but the whole width (local compressing of sleepers);

c) loading affects part of the sample length and width (so called local compressing "under bolt").

Compressing parallel to grain for different species and compressing perpendicular to grain for conifers and diffuse - porous broadleaves wood has been analyzed rather comprehensively. Data on the strength of ring-porous deciduous perpendicular to grain (Fig. 1) is very scarce – usually strength of wood in the case of local grabbing is presented (Fig. 1 – 3) [7]. In the literature can be obtained data, which describe compression strength of some ring-porous deciduous trees perpendicular to grain, which were growing and studied in the USA and Canada [8]. However,

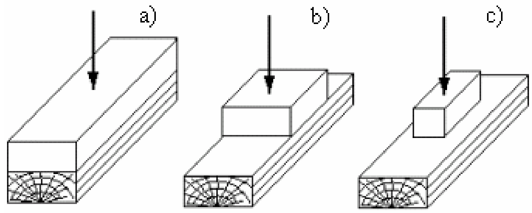

Fig. 1. Cases of wood compressing perpendicular to grain [6]

it remains unknown in what direction (radial or tangential) the wood was compressed and what methods were applied in the studies. Absence of the data lead to the studies of oak and ash (both of which are ring-porous) resistance to compression perpendicular to grain, when loading is evenly distributed on the whole surface (Fig. 1). Therefore, further on only the first case of compressing perpendicular to grain is discussed.

During compression perpendicular to grain two types of deformations are possible: one-phase (characteristic for conifers compressed in tangential direction) and three-phase, which is characterised by a more complicated diagram (Fig. 2) [6]. This deformation is characteristic for conifers compressed in radial direction and deciduous compressed in both directions (radial and tangential). In the case of three-phase deformation, 3 stages are observed in the diagram. The initial one is a straight segment, which shows that Hook's law is applicable to wood and it becomes deformed similarly to the case of one-phase deformation. This is called the first phase of deformation: when compressing conifers in radial direction, the first to deform is the early wood of annual rings. This phase lasts until the walls of early tracheids loose stability and start crumpling, then follows the second phase. After the walls of early tracheids loose their stability, not much strength is needed to crample them (loading may not increase any more or may only slightly increase). At the same time starts deformation of late tracheids – the second phase gradually passes into the third phase. During the third phase wood becomes deformed due to the compression of late tracheids.

*Corresponding author. Tel.: + 370-37-353863; fax.: +370-37-353989.
E-mail address: *medkat@dtf.ktu.lt* (I. Juodeikienė)

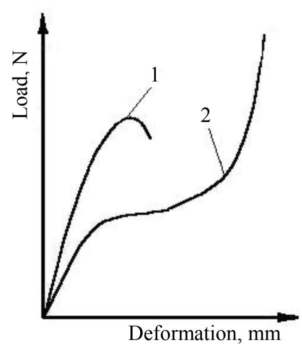

Fig. 2. Deformation types of wood compressed perpendicular to grain: 1 – one-phase, 2 – three-phase [6]

Sample failure may be observed only in the case of one-phase deformation. Under three-phase deformation, wood may be pressed even down to 1/4 of its initial height, while destruction signs may be absent. Usually, the parameter, which characterize compressing perpendicular to grain, is so called "relative strength" (f). It is the point, where proportional deformation passes into accelerated deformation. In the diagram of loading and deformation (Fig. 3), it is a point, where tangent of the angle of curve with the vertical line increases 1.5 times ($\text{tg}\gamma = 1.5\ \text{tg}\beta$). During experiment it is ascertained according to a sudden increment of sample deformation.

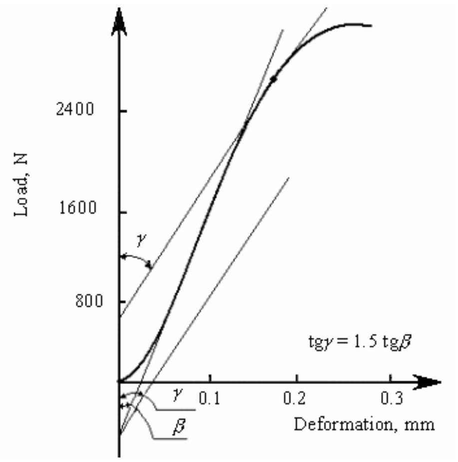

Fig. 3. Diagram of loading and deformation [6]

Compressing deciduous, three-phasiness of the diagram is not so obvious, but still observable. For oak, compressed in the radial direction, due to the influence of wide medullary rays, one-phase deformation is observed. Wood sample in this case swells on the side of ring protuberance.

Relative strength during compression (MPa) is calculated as follows:

$$f = \frac{F}{a \cdot L} \ , \qquad (1)$$

where F is the force, corresponding to the limit of proportionality, a and L are the width and length of the sample, respectively.

Relative strength of all species compressed perpendicular to grain is on an average about 10 times less than compressed parallel to grain. Relative strength during local compressing is 20 – 25 % higher than during compression [6, 8]. Here additional resistance of the grain contributes to bending under punch's edges. Testing the wood with a special stamp, which transfer load only to a certain part of sample length and width (Fig. 1), relative strength is still slightly higher, due to grain resistance to splitting. However, as it has been mentioned, wood resistance to compression perpendicular to grain and to crampling is investigated only insufficiently.

Wood resistance to compression (as well as other physical and mechanical properties) depends also on its microstructure. Dimensions of individual structural elements of wood influences its strength, i.e. the more elements and the thicker their walls, the higher is wood strength. On the base of presented data [10], it is stated that increase of wall thickness of late tracheids by 36 % for pine wood and by 30 % for larch wood, density increases respectively by 18 and 20 %. Meanwhile compression strength parallel and perpendicular to grain increases by 83 and 70 %. Due to pores present in the early wood, the ability of ring-porous deciduous to bend increases, also. As far as this zone may increase in density, wood during bending fails an can be destroyed. However, pores are thin-walled elements and they reduce wood strength. Medullary rays consist of thin-walled cells, so big amount of them worsens wood properties (causes uneven drying, increases wood splitting, etc.). During compression perpendicular to grain, medullary rays have positive influence. Compression strength of deciduous wood (which has wide rays) in radial direction is higher [10]. Thus, due to the influence of wide medullary rays, during compression of oak wood in radial direction, one-phase deformation is observed.

Great influence on wood strength has the amount of late wood in annual rings. The color of early and late wood in deciduous trees is almost the same, but its density differs. Early wood is much more porous. It is especially obvious in the cross-sections of oak and ash wood. Late wood is essentially comprised of mechanical elements, therefore its density and mechanical properties are 2 – 3 times higher than those of early wood [6].

Width of annual rings (or their amount per length (usually per 1 cm)) also influences physical and mechanical properties of wood. The distinctness of annual rings in various species differs. Their width varies. It depends not only on the tree species, but also on the age, climate, growth conditions, *etc*. In the wood of ring-porous deciduous the width of annual rings is greater in places where late wood is more developed. That leads to assumption, that increase width of annual rings, should improve mechanical properties.

The aim of this work is to ascertain relative strength of oak and ash wood and its dependence on the number of annual rings in sample cross-section.

EXPERIMENTAL

Oak wood was dried in the drying chamber down to 7.2 – 8.2 %, while that of ash was down to 6.6 – 7.7 % of moisture content. Cross-section of the samples was 20×20 mm, length was 30 mm; conventional density of oak wood samples was 600 – 640 kg/m^3 and for ash wood it was 545 – 660 kg/m^3, number of annual rings in the cross-section of samples varied from 4 to 14. Cross-section of the samples is too small to eliminate the influence of ring crookedness. They were sawn in such way, that annual rings in cross-sections were parallel to one pair of sample edges, while longitudinal axis coincides with the direction of the grain. The samples containing less defect were used for the study.

According to the number of annual rings in the cross-section, oak and ash wood samples were divided in to 4 groups (Table 1).

Table 1. Grouping of samples according to the number of annual rings in sample cross-section

Groups	Number of annual rings in sample cross-section	Conventional density, kg/m^3	
		Oak wood	Ash wood
1	4	640	568
2	5…6	595	557
3	7…10	601	541
4	11…14	642	541

Before the study dimensions of samples *a* (width) and *L* (length) at the axes of symmetries were measured with 0.1 mm of accuracy. When sample was compressed in radial direction, sample width *a* was measured in tangential direction, while compressing in tangential direction, sample width *a* was measured in radial direction.

RESULTS AND ANALYSIS

Oak wood sample, compressed in tangential direction, and ash wood samples, compressed in both radial and tangential directions, deform according to the three-phase deformation. Three-phase of the diagram is not so vivid, but still observable (Fig. 4, 5).

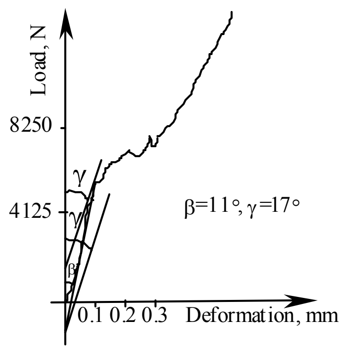

Fig. 4. Deformation diagrams of ash wood compressed in radial direction

Due to the influence of wide medullary rays, one-phase deformation is observed compressing oak wood in radial direction (Fig. 6). However, during the study it was observed, that some oak wood samples, compressed in radial direction, deformed according to the three-phase deformation (Fig. 7). Therefore, two strength ascertainment variants of compressed oak wood in radial direction were singed out: variant I – it is assumed, that oak wood in radial direction deformed strictly according to the one – phase deformation pattern; variant II – it is assessed, that some samples followed three-phase deformation.

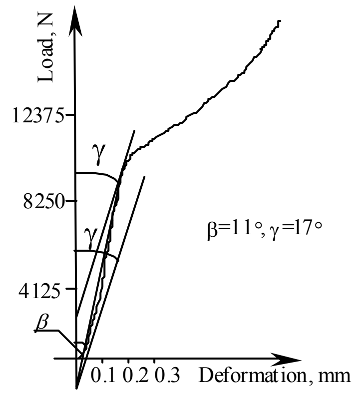

Fig. 5. Deformation diagrams of ash wood compressed in tangential direction

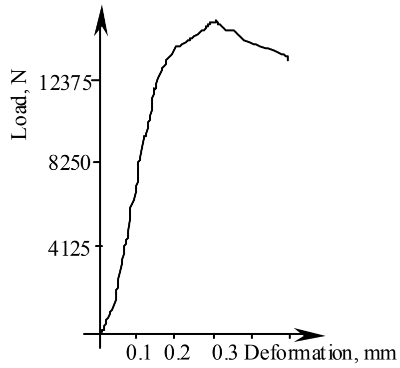

Fig. 6. One-phase deformation diagrams of oak wood compressed in radial direction

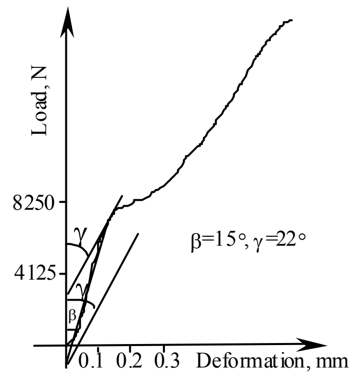

Fig. 7. Three-phase deformation diagrams of oak wood compressed in radial direction

Compressing in tangential direction of oak and in both tangential and radial directions of ash wood, force corresponding to the limit of proportionality is obtained from loading and deformation diagrams. The highest strength values were found compressing oak wood samples in radial direction. For them one phase deformation mechanism was characteristic. Afterwards, the strength of oak and ash wood (in the case of three-phase deformation – relative strength) after compressing perpendicular to grain was calculated according to (1) formula. As far as moisture content of the studied samples varied from 6.6 up to 8.2 % (i.e. it was not normalized and equal to 12 %), compression strength was recalculated into strength for normalized moisture content according to the equation:

$$f_{12} = f_\omega [1 + k(\omega - 12)], \quad (2)$$

where k is the coefficient, which depends on the kind of experiment: compressing perpendicular to grain, independently on the biological species of wood, it is equal to 0.035, ω is moisture content in the wood.

Study results are presented in Table 2 and Figure 8.

Table 2. Strength of oak and ash wood compressed perpendicular to grain, MPa

Group number	Oak wood			Ash wood	
	Radial direction		Tan-gential direction	Radial direction	Tan-gential direction
	Var. I	Var. II			
average	**21.56**	**21.33**	**9.43**	**10.73**	**15.25**
1 gr.	24.24	24.31	10.89	15.47	13.82
2 gr.	23.51	24.04	9.49	13.71	14.61
3 gr.	19.9	20.24	9.08	9.90	15.57
4 gr.	16.11	16.41	9.31	9.97	14.92

Relative deviation d_α (under confidence probability $\alpha = 0{,}95$) of arithmetic mean $\overline{x}$ of oak and ash wood compression strength perpendicular to grain varied from 1 to 3 %, variation coefficient V varied from 7.58 to 16.71 %. As far as variation coefficient $V \leq 30$ %, can be considered, that dispersion of the results is small and the obtained results are sufficiently precise and reliable.

Compression strength of oak wood, mean conventional density of which is 613 kg/m^3 (in separate samples – from 600 to 640 kg/m^3), in radial direction is 21.45 MPa, in tangential direction this one is 9.43 MPa. Strength of ash wood, mean conventional density of which comprises 555 kg/m^3 (in separate samples vary from 545 to 660 kg/m^3), during compression in radial direction comprises 10.73 MPa, while in tangential direction it reaches 15.25 MPa.

The strength of oak wood compressed perpendicular to the grain is 2 times (or from 1.6 to 2.2 times comparing individual groups according to the number of annual rings in sample cross-section) higher than the strength of ash wood in radial direction. However, the strength of oak wood compressed in tangential direction, is 1.6 times (or from 1.3 to 1.8 times comparing separate groups according to the number of annual rings in sample cross-section) lower than that of ash wood.

Due to wide medullary rays, strength during of compression of oak wood perpendicular to grain in radial direction is 2.3 times higher (or from 1.7 to 2.5 times comparing separate groups according to the number of annual rings in sample cross-section) than those compressing in tangential direction.

Results in Table 2 and Figure 8 show, that strength of compressed in radial direction oak wood, when the width of annual rings is the greatest, is the highest as well ($f_{o,r}$ = 24.24 MPa). Further on, the increase of number of annual rings in the sample cross-section, decreases the strength of wood. Strength, when cross-section contains 4 annual rings, is 50 % higher than strength, of samples of annual rings in which is bigger or equal to 11 ($f_{o,r}$ = 16.11 MPa).

Compression strength of oak wood in radial direction in the case of variant I, when deformation mode of all samples was considered to be one-phase, is up to 2 % higher than in the case of variant II, when three-phase deformation was observed in some samples. In the case of variant II, similar as in variant I, strength of oak wood during compression perpendicular to grain is highest ($f_{o,r}$ = 24.31 MPa) when the width of annual rings is biggest. Strength of samples which cross-section contains 4 rings is 48 % higher, than strength of samples for which number of rings is bigger or equal to 11 ($f_{o,r}$ = 16.41 MPa).

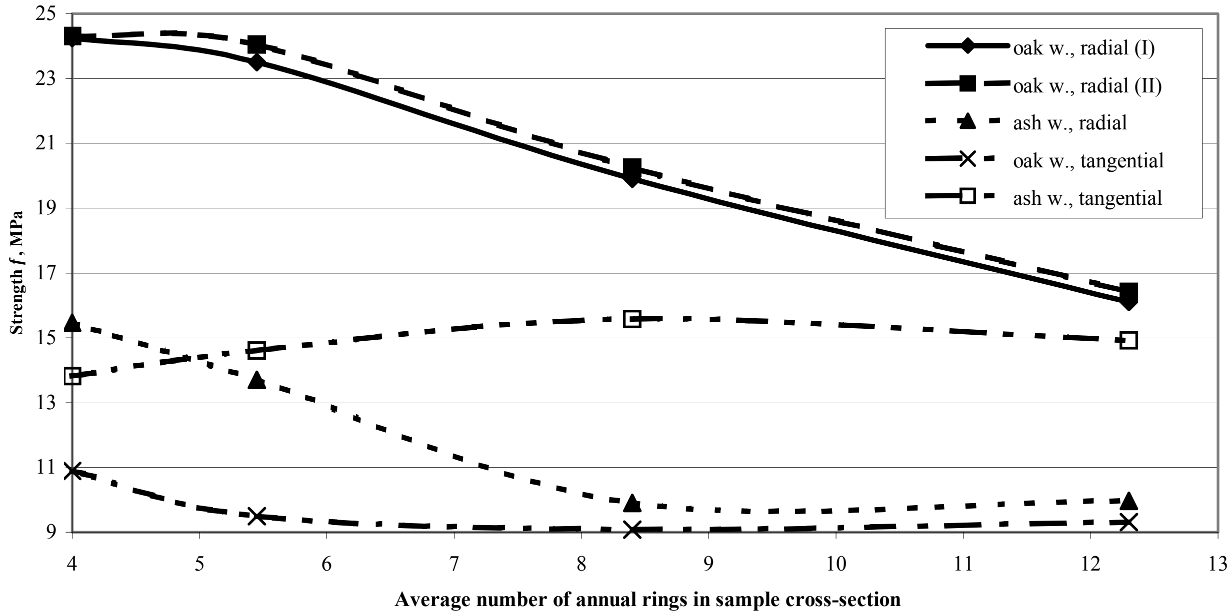

Fig. 8. Dependence of oak and ash wood compression strength perpendicular to grain on the number of annual rings in sample cross-section

Table 3. Coefficients of polynomial equations

Coefficients	Oak wood			Ash wood	
	Radial direction		Tangential direction	Radial direction	Tangential direction
	Var. I	Var. II			
a	0.0206	0.031	–0.0187	0.0355	–0.006
b	–0.5115	–0.7841	0.5284	–0.6762	0.0644
c	2.9119	5.1096	–4.7152	2.8251	0.3257
d	19.458	14.43	22.497	12.715	11.872
$R^2_{polynomic}$	1	1	1	1	1
e	–0.9339	–0.9265	–0.1359	–0.756	0.1451
f	28.154	28.407	10.742	17.819	13.664
R^2_{linear}	0.9928	0.9845	0.4412	0.8274	0.4465

The highest strength $f_{o,t}$ = 10.89 MPa of oak wood (see Table 2 and Fig. 8) compressed in tangential direction is also obtained when sample contains 4 annual rings. Here the tendency of strength decrease with increasing number of annual rings in sample cross-section is observed. Strength when the number of annual rings is bigger or equal to 11, equals $f_{o,t}$ = 9.31 MPa, and it is by 17 % less than strength when sample cross-section contains 4 rings.

Compression strength of ash wood in radial direction is 1.4 times (or from 1.2 to 1.5 times comparing separate groups according to the number of annual rings in sample cross-section) lower than compression strength in tangential direction.

After compression of ash wood in radial direction, highest strength values ($f_{a,r}$ = 15.47 MPa) is obtained when the width of annual rings is lowest (i.e. sample cross-section contains 4 rings). It decreases by 55 % when the number of annual rings in sample cross-section comprises bigger or equal to 11 ($f_{a,r}$ = 9.97 MPa). While compressing ash wood in tangential direction, the dependence between strength changes and number of annual rings is insignificant. The highest strength, compressing in tangential direction ($f_{a,t}$ = 15.57 MPa), is attained when the number of annual rings in sample cross-section vary from 7 to 10.

Curves presented in Fig. 6 may be mathematically described. The most precise description is achieved through (R^2 = 1) a third order polynomial equation (3), but it may be described also by linear dependence (equation) (4).

$$y = ax^3 + bx^2 + cx + d\,; \quad (3)$$

$$y = ex + f. \quad (4)$$

The values of coefficients are presented in Table 3.

CONCLUSIONS

Strength of oak wood compressed in radial direction is $f_{o,r}$ = 21.45 MPa, in tangential direction that is $f_{o,t}$ = 9.43 MPa. This one for ash wood is $f_{a,r}$ = 10.73 MPa and $f_{a,t}$ = 15.25 MPa in radial and tangential directions, respectively.

Strength of oak wood compressed in radial direction is 2 times higher than the strength of ash wood, however, compressing in tangential direction – strength of oak wood is 1.6 times higher than that of ash wood.

Strength of oak wood, due to the influence of wide medullary rays, compressed in radial direction is 2.3 times higher than those compressed in tangential direction. Strength of ash wood compressed in radial direction is 1.4 times less than strength of wood compressed in tangential direction.

The increase of number of annual rings in sample cross-section (from 4 to 14), i.e. the decrease width of annual rings, results on the decrease strength of oak wood compressed in radial and tangential directions as well as strength of ash wood compressed in radial direction. It was determined that strength of oak and ash wood compressed in radial direction decreases up to 50 – 55 %, that of oak wood compressed in tangential direction decreases up to 17 %, when number of annual rings increases. It is explained by the fact, that the width of annual rings in the wood of ring-porous deciduous is in places where late wood is better developed and is characterized by 2 – 3 times higher density and better mechanical properties than early wood.

REFERENCES

1. **Fridley, K. J., Mitchell, J. B., Hunt, M. O., Senft, J. F.** Effect of 85 Years of Service on Mechanical Properties of Timber Roof Members. Part 2. Cumulative Damage Analysis *Forest Products Journal ISSN 0015-7473* 46 (6) 1996: pp. 85 – 90.
2. **McDonald, K. A., Hassler, C. C., Hawkins J. E., Pahl, T. L.** Hardwood Structural Lumber from Log Heart Cants *Forest Products Journal ISSN 0015-7473* 46 (6) 1996: pp. 55 – 62.
3. Wood Engineering and Construction Handbook (Editors Faherty, K. F., Williamson, T. G.). New York, McGRAW-HILL Inc., 1999: 912 p.
4. The Wood Book. From the Original Editions at Royal Botanic Gardens Kew, London, 2002: 864 p.
5. The Encyclopedia of Wood. Revised Edition. New York, Sterling Publishing Co. Inc., 1989, 466 p.
6. **Jakimavičius, Č.** Medienotyra (Wood Science). Kaunas, 2002: 272 p. (in Lithuanian).
7. **Melechov, V. I., Pobolskaja, V. L.** Wood Destruction and Deformation Process Compressing Perpendicular to Grain *Forestry Journal ISSN 0536-1036* 2 – 3 1999: pp. 120 – 123 (in Russian).
8. **Volynskyj, V. N.** Interrelationship and Changeability of Physico-Mechanical Properties of Wood. Arkangelsk, 2000: 196 p. (in Russian).
9. **Morkevičius, A., Papreckis, B.** Wood and Its Products. 2004: 102 p. (in Lithuanian).
10. **Perelygin, L. M., Ugoliov, B. N.** Wood Science. Moscow, 1971: 288 p. (in Russian).