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ELASTIC MODULI OF VENEERS IN PINE AND BEECH PLYWOOD

The paper presents the results of a study concerning the elastic moduli of veneers assembled in pine and beech plywood panels. The elastic modulus of veneers in the direction of the grain and the elastic modulus of veneers in the direction perpendicular to the grain were determined by bending plywood strips with their longitudinal axis parallel and perpendicular to the grain of the face plies. The effects of a resin type and the number of veneer plies in the plywood were evaluated. Three- and five-ply plywood bonded with urea and phenol resins were tested. The effect of glue lines in the plywood on the veneer elastic moduli was also evaluated.

Keywords: veneer, plywood, elastic modulus, pine wood, beech wood

Introduction

Plywood is regularly used for many applications. It is a wood-based material with good performance and important strucural parts are made of it. The elastic properties of entire plywood are fairly well known, whereas those of veneer in plywood are poorly understood. It is worth noting that the properties of veneers assembled in plywood panels differ from the properties of veneers before pressing. The veneers in plywood have a greater density as a result of their compaction and adhesive diffusion into the wood [Mansouri et al. 2006].

The elastic moduli of veneer in plywood have rarely been the subject of study. Curry and Hearmon [1967] determined the elastic moduli of veneers in three-ply plywood made of gaboon (*Aucoumea klaineana*) and other wood species from Commonwealth countries. They calculated these moduli basing on elastic moduli in the bending of the plywood strips with the longitudinal axis parallel and perpendicular to the grain of the face plies. Okuma [1976] calculated the elastic moduli of veneer in Hoop pine (*Araucaria cunninghamii*) plywood. He used the method of comparing theoretical and empirical equations for elastic moduli in the bending of the plywood strips.

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Wilczyński [2007] determined the elastic moduli of veneers in beech plywood basing their analysis like Curry and Hearmon [1967] on elastic moduli in the bending of two plywood strips with different longitudinal axes, and taking into account the glue lines that bonded the veneers. The method required the assumption of anisotropy of veneer elasticity expressed as a ratio of veneer elastic modulus in the grain direction to that modulus in the direction perpendicular to the grain. This method was also used for evaluating the effect of the thicknesses of glue lines on the elastic moduli of veneer in beech plywood [Wilczyński et al. 2008]. Moreover, the effect of veneer anisotropy on the elastic moduli of veneers in plywood determined by this method was examined [Wilczyński, Warmbier 2009]. In the previous study [Wilczyński 2011], the author used a simplified method for determining the veneer elastic moduli, neglecting the effect of the glue lines bonding veneers.

The elastic properties of the veneer before making up plywood, under free conditions, were studied by Lang et al. [2003]. They determined Young's modulus for different directions in the veneer plane, using an ultrasound stress-wave method. The veneers of five hardwood species were the subject of the study but these species did not contain beech wood.

Veneer elastic moduli data can be useful for an analysis of stresses in the construction parts made of plywood, and also for application of the theory of the layered systems. These moduli are affected by many factors. The objective of this study was to evaluate the effects of wood species, a resin type and the number of veneer plies in plywood on the veneer elastic moduli.

Materials and methods

The plywood panels for this study were fabricated in a laboratory using selected pine (*Pinus silvestris* L.) and beech (*Fagus silvatica* L.) veneers 50 cm by 50 cm, without defects, of 1.5 mm thickness. The moisture content of the veneers (according to EN 322) was approx. 7%, and the average density (according to EN 323) of the pine and beech veneers were 0.48 and 0.63 g/cm^3, respectively.

Two types of adhesive, a phenol and an urea resin, were used to bond the veneers. Their physical properties are given in table 1. The formulation of the phenol adhesive was:
 – phenol-formaldehyde resin … 100 parts by weight,
 – water … 10.5 parts by weight,
 – rye flour with tannin … 14 parts by weight,
and that of the urea adhesive was:
 – urea-formaldehyde resin … 100 parts by weight,
 – water … 20 parts by weight,
 – rye flour … 10 parts by weight,
 – hardener MZ … 10 parts by weight.

Table 1. Properties of resins and adhesive masses
Tabela 1. Właściwości żywic i mas klejowych

Property *Właściwość*	Standard *Norma*	Unit *Jed- nostka*	Phenol-formaldehyde *Fenolowo-formaldehydowa*		Urea-formaldehyde *Mocznikowo-formaldehydowa*	
			resin *żywica*	adhesive mass *masa klejowa*	resin *żywica*	adhesive mass *masa klejowa*
dynamic viscosity *lepkość dynamiczna*	PN-92/C-89402	mPa·s	340	1450	1630	2100
dry mass content *zawartość suchej masy*	EN 827	%	48.4	-	68.1	-
gelation time *czas żelowania*	BN-67/6317-01 BN-75/6327-01	s	-	235	-	75

Three- and five-ply panels were made, using standardized procedures that simulated industrial production. The adhesive spread was 160 g per 1 m². The panels were pressed with 1.6 MPa for 4 and 6 min for the three- and five-ply panels, respectively. The press temperature was 135 and 100°C for the plywood bonded with phenol and urea resins, respectively. Prior to testing, all the panels were stored in controlled conditions (50% relative humidity and 20°C) for two weeks.

The compression ratio of plywood was calculated as:

$$cr = \frac{\Sigma t_v - t_p}{\Sigma t_v} \times 100\%$$ (1)

where: Σt_v = total thickness of the veneers before pressing,

t_p = thickness of plywood panel after pressing and conditioning.

Two kinds of specimens were cut from the plywood panels, one with the longitudinal axis parallel and the other with that axis perpendicular to the grain of face veneers. These specimens were 50 mm wide, and 170 and 210 mm long for the three- and five-ply panels, respectively. Fifteen specimens for each species, adhesive type, number of plies, and specimen axis direction were prepared.

Plywood is the layered system which consists of compressed veneers and glue lines. The flexural rigidity of plywood is the sum of the rigidities of its layers:

$$EI = \sum E_i I_i$$ (2)

where: E = modulus of elasticity of plywood,

I = moment of inertia of the full cross section about its neutral axis,

E_i = modulus of elasticity of the ith layer (veneer or glue line),

I_i = moment of inertia of the cross section of the ith layer about the neutral axis of the full cross section.

Consider the plywood strips subjected to bending, in which the grain direction of the face plies runs parallel or perpendicular to the longitudinal axis of the strip (fig.1): when glue lines are neglected, the flexural rigidity of the strip is the sum of the rigidities of the plies with the longitudinal axis parallel to their grain and the plies with that axis perpendicular to their grain:

$$E_1 I_2 = E_x I_{2x} + E_y I_{2y} \tag{3}$$

$$E_2 I_1 = E_y I_{1y} + E_x I_{1x} \tag{4}$$

where: E_1 and E_2 = modulus of elasticity in the bending of the plywood strip with the longitudinal axis parallel and perpendicular to the grain direction of the face plies, respectively,

I_2 and I_1 = moment of inertia of the cross section of the plywood strip with the longitudinal axis parallel and perpendicular to the grain direction of the face plies about the neutral axis 2 and 1, respectively,

E_x and E_y = Young's modulus of the veneer in the grain and perpendicular to grain directions, respectively,

I_{2x} and I_{1x} = moment of inertia of all the veneer plies with the longitudinal axis parallel to the grain about the neutral axis 2 and 1, respectively,

I_{2y} and I_{1y} = moment of inertia of all the veneer plies with the longitudinal axis perpendicular to the grain about the neutral axis 2 and 1, respectively.

Assuming that all compressed veneers are of the same thickness, one obtains:

$$I_1 = I_2, \qquad I_{1y} = I_{2x}, \qquad I_{1x} = I_{2y} \tag{5}$$

Using the following factors:

$$A = \frac{I_{2x}}{I_2} = \frac{I_{1y}}{I_1}, \qquad\qquad B = \frac{I_{2y}}{I_2} = \frac{I_{1x}}{I_1} \tag{6}$$

and combining eqs (3) – (6) gives the relations:

$$E_1 = AE_x + BE_y \tag{7}$$
$$E_2 = AE_y + BE_x \tag{8}$$

which can be rearranged to expressions for the Young's moduli of the veneer:

$$E_x = \frac{AE_1 - BE_2}{A^2 - B^2} \tag{9}$$

$$E_y = \frac{AE_2 - BE_1}{A^2 - B^2} \qquad (10)$$

Eqs (9) and (10) permit the calculation of Young's moduli E_x and E_y of the veneer through the experimental determination of elastic moduli E_1 and E_2 of plywood strips.

The tested plywoods were multilayered structures consisting of veneers (plies) and glue lines. When Young's moduli E_x and E_y were determined the glue lines were neglected as too thin when compared to the veneers. If the glue lines are considered, eqs (3) and (4) take the following form:

$$E_1 I_2 = E_x^* I_{2x}^* + E_y^* I_{2y}^* + E_g I_g \qquad (11)$$

$$E_2 I_1 = E_y^* I_{1y}^* + E_x^* I_{1x}^* + E_g I_g \qquad (12)$$

where: E_x^* and E_y^* = Young's modulus of the veneer in the grain and perpendicular to grain direction, respectively,

I_{2x}^* and I_{2y}^* = moment of inertia of all the veneer plies with the longitudinal axis parallel and perpendicular to the grain about the neutral axis 2, respectively,

I_{1x}^* and I_{1y}^* = moment of inertia of all the veneer plies with the longitudinal axis parallel and perpendicular to the grain about the neutral axis 1, respectively,

E_g = Young's modulus of the glue line,

I_g = moment of inertia of all the glue lines about the neutral axis.

Using the following factors:

$$A^* = \frac{I_{2x}^*}{I_2}, \qquad B^* = \frac{I_{2y}^*}{I_2}, \qquad C^* = \frac{I_g}{I_2} \qquad (13)$$

and rearranging eqs (11) and (12), one obtains the expressions for Young's moduli of the veneer:

$$E_x^* = \frac{A^* E_1 - B^* E_2 - \left(A^* - B^*\right) C^* E_g}{A^{*2} - B^{*2}} \qquad (14)$$

$$E_y^* = \frac{A^* E_2 - B^* E_1 - \left(A^* - B^*\right) C^* E_g}{A^{*2} - B^{*2}} \qquad (15)$$

The factors A^*, B^* and C^* depend on the thicknesses of the veneers and the glue lines in the plywood. For the five-ply beech plywood bonded with the phenol

adhesive, the average veneer and glue line thicknesses determined by microscopic measurements were 1.33 and 0.07 mm, respectively [Wilczyński 2011]. The factors A^*, B^* and C^* calculated by eqs (13) on the basis of these thicknesses were equal to 0.773, 0.202 and 0.025, respectively.

The moduli E_1 and E_2 were determined in the bending test, as shown in fig. 2, using an Instron 3367 machine and a deflectometer measuring the deflection with an accuracy of 0.001 mm. The span l was equal to 24 times the thickness t_p of plywood, the distance l_1 for measuring the specimen deflection was 5/6 of the distance between the loading heads. The bending speed was 2 mm/min. The values of the moduli E_1 and E_2 were calculated using the formulas:

$$E_1 = \frac{l_1^2 l_2 \Delta F}{16 I_2 \Delta w} \ , \quad E_2 = \frac{l_1^2 l_2 \Delta F}{16 I_1 \Delta w} \qquad (16)$$

where: ΔF = increment of load on the straight line portion of the load-deflection curve,
  Δw = increment of deflection corresponding to ΔF.

The obtained data were statistically analyzed using the Statistica version 10. A two-way analysis of the variance (ANOVA) was conducted to determine the significance of the effects of wood species and adhesive type on the moduli E_1 and E_2. Tukey's test was also applied to evaluate the statistical significance between the mean values of the moduli of plywood made from the different wood species and resin types.

Results

The results of the bending tests, the mean values and the standard deviations of the elastic moduli of the examined plywood, are given in table 2. The results of the ANOVA analysis showed that both moduli E_1 and E_2 only depend significantly on veneer wood species (table 3). Tukey's test results are shown in table 1. The values with different letters for given modulus are significantly different at the 5% significance level.

Considering the results of the statistical analysis, the specimens with phenol and urea adhesives were included in one group. The mean values of the moduli E_1 and E_2 for these groups were the basis for calculating Young's moduli of the veneer, in the grain direction, E_x, and in the direction perpendicular to grain, E_y, in plywood expressed by eqs (9) and (10) (table 4). The factors A and B, expressed by eqs (6), were equal to 0.963 and 0.037, respectively, for the three-ply plywood, and 0.792 and 0.208, respectively, for the five-ply plywood.

The moduli E_x and E_y of the veneer in the 5-ply plywood are about 4% and 5% greater than those in the three-ply plywood, for the pine and beech plywood, respectively. This is the result of a greater compression of five-ply plywood (table 4).

Table 2. Elastic moduli of tested plywood
Tabela 2. Moduły sprężystości testowanych sklejek

Wood species *Gatunek drewna*	Resin type *Rodzaj żywicy*	Three-ply plywood *Sklejka trzywarstwowa*		Five-ply plywood *Sklejka pięciowarstwowa*	
		modulus E_1 (MPa) *moduł E_1 (MPa)*	modulus E_2 (MPa) *moduł E_2 (MPa)*	modulus E_1 (MPa) *moduł E_1 (MPa)*	modulus E_2 (MPa) *moduł E_2 (MPa)*
pine *sosna*	urea-formaldehyde *mocznikowo-formaldehydowa*	13790 (1260)a	1050 (110)a	11730 (1030)a	3520 (320)a
	phenol-formaldehyde *fenolowo-formaldehydowa*	13940 (920)ab	1070 (100)a	11910 (910)a	3540 (290)a
beech *buk*	urea-formaldehyde *mocznikowo-formaldehydowa*	14580 (850)ab	1450 (130)b	12560 (740)ab	4050 (290)b
	phenol-formaldehyde *fenolowo-formaldehydowa*	14970 (1290)b	1510 (150)b	12880 (960)b	4140 (220)b

Numbers in parentheses are standard deviations
W nawiasach odchylenia standardowe
Values within the same line column followed by different letters are significantly different at $P<0.05$
Wartości w tej samej kolumnie oznaczone różnymi literami różnią się istotnie przy $P<0.05$

Table 3. Two-way ANOVA test on the effects of wood species and resin type on plywood elastic moduli (p-values)
Tabela 3. Dwuczynnikowy test ANOVA wpływu gatunku drewna i rodzaju żywicy na moduły sprężystości sklejki

Variable *Zmienna*	Three-ply plywood *Sklejka trzywarstwowa*		Five-ply plywood *Sklejka pięciowarstwowa*	
	modulus E_1 *moduł E_1*	modulus E_2 *moduł E_2*	modulus E_1 *moduł E_1*	modulus E_2 *moduł E_2*
wood species *gatunek drewna*	0.0018^*	$<0.0001^*$	0.0004^*	$<0.0001^*$
resin type *rodzaj żywicy*	0.3323^{ns}	0.1001^{ns}	0.2901^{ns}	0.4479^{ns}
wood species x resin type *gatunek drewna x rodzaj żywicy*	0.6692^{ns}	0.2261^{ns}	0.7634^{ns}	0.5864^{ns}

*Denotes significance at 0.01; ns - not significant at 0.05
Oznacza istotność przy 0.01; ns - nieistotny przy 0.05

Table 4. Elastic moduli of veneers in plywood
Tabela 4.Moduły sprężystości fornirów w sklejce

Wood species Gatunek drewna	Number of plies Liczba warstw	Modulus E_x (MPa) Moduł E_x (MPa)	Modulus E_y (MPa) Moduł E_y (MPa)	E_x/E_y	Compression ratio of plywood (%) Stopień sprasowania sklejki (%)
pine	3	14380	550	26.2	5.5
sosna	5	14780	580	25.5	9.2
beech	3	15310	950	16.1	4.3
buk	5	15790	1020	15.5	7.0

The moduli of the beech veneer are greater than those of the pine veneer. The modulus E_x of the beech veneer is slightly, approx. 7% greater, whereas the modulus E_y is considerably greater, about 74%. This disproportion is related to the anisotropy of the elastic properties of the veneer in the plywood, which can be expressed by the E_x/E_y ratio. This ratio amounts to about 26 for the pine veneer and to about 16 for the beech veneer (table 4). The E_x/E_y ratio for the veneer in the plywood can be compared with the E_L/E_T ratio for wood. For softwood in general the E_L/E_T ratio range is from 20 to 24 [Bodig, Goodman 1973; Bodig, Jayne 1993]. For hardwood, the anisotropy of elasticity in the plane *LT* is smaller than for softwood, therefore the E_L/E_T ratio is smaller. According to Hearmon [1948], for the beech wood with the density of 0.75 g/cm³, moisture content of 11%, and modulus E_L of 13700 MPa, the E_L/E_T ratio is equal to 12. The greater E_x/E_y ratio for the veneer compared to the E_L/E_T ratio for the wood is probably due to peeler checks caused by the rotary-cut processing.

In comparing the determined moduli E_x and E_y of the veneer in tested plywood with the moduli E_L and E_T of beech and pine wood, it is found that the average values of the moduli E_x and E_y of the veneer in beech plywood are 15550 and 985 MPa, respectively, whereas the values of the moduli E_L and E_T of beech wood with a density of 0.75 g/cm³ and a moisture content of 11% are 13700 and 1140 MPa [Hearmon 1948], respectively. Thus, the value of E_x is greater than the value of E_L, and the value of E_y is smaller than the value of E_T. The average values of the moduli E_x and E_y of the veneer in pine plywood are 14580 and 565 MPa, respectively. The values of the moduli E_L and E_T of beech wood are 16300 and 570 MPa, respectively for wood with a density of 0.55 g/cm³ and a moisture content of 10% [Hearmon 1948], and 12100 and 480 MPa for wood with a density of 0.49 g/cm³ and a moisture content of 12% (Leontiev 1952). Therefore, the values of the moduli E_x and E_y of the veneer in pine plywood are smaller than the values of the moduli E_L and E_T of pine wood with a density of 0.55 g/cm³ and greater than those of pine wood with a density of 0.49 g/cm³. It should be noticed that the above comparisons have a limited importance. As it has been pointed out in this paper, the properties of veneers assembled in plywood dif-

fer from those of the wood from which the veneers were made. Moreover, the elastic moduli of a given wood species are affected by many factors, particularly by its density

In order to calculate the veneer moduli E_x^* and E_y^*, the modulus E_g of a glue line should be known. As there are no data about E_g in literature it was assumed that the value of this modulus can range from 1000 to 10000 MPa. The values of the veneer moduli E_x^* and E_y^* for the five-ply beech plywood bonded with the phenol adhesive calculated by eqs (14) and (15) are given in table 5 and compared with the veneer moduli E_x and E_y obtained when the glue lines were neglected. The values of the E_x^* are greater than those of the E_x but the relative difference between these values is very small and ranges from 0.9 to 2.3%. The relative difference between the veneer moduli E_y^* and E_y is greater and ranges from 1.9 to (-19.4%). For other tested plywood these differences are similar. In general, it can be concluded that the effect of the glue lines on the results of the determination of Young's moduli of veneer in plywood is negligible.

Table 5. Comparison of Young's moduli of veneer in plywood calculated by considering and neglecting the glue lines; E$_g$ = Young's assumed modulus of glue line
Tabela 5. Porównanie modułów Younga forniru w sklejce obliczonych przy uwzględnieniu i pominięciu spoin klejowych; E$_g$ = założony moduł Younga spoiny klejowej

E_g (MPa)	E_x (MPa)	E_x^* (MPa)	$\dfrac{E_x^*-E_x}{E_x}\times100(\%)$	E_y (MPa)	E_y^* (MPa)	$\dfrac{E_y^*-E_y}{E_y}\times100(\%)$
1000		16360	2.3		1050	1.9
5000	15990	16250	1.6	1030	950	-7.8
10000		16130	0.9		830	-19.4

Conclusions

The elastic moduli in the bending of plywood strips, the modulus of the strip with the longitudinal axis parallel and the modulus of the strip with the longitudinal axis perpendicular to the grain direction of the face plies, are influenced by the wood species and are not influenced by the resin type.

The elastic moduli of the veneers in five-ply plywood, the modulus in the grain direction and the modulus in the direction perpendicular to the grain, are slightly greater than those in three-ply plywood. The moduli of the beech veneer are greater than those of the pine veneer. The anisotropy of the elastic properties of the veneer in the veneer plane, expressed by the ratio of the modulus in the grain direction to the modulus in the direction perpendicular to the grain, is greater for pine than for beech veneer. The effect of the glue lines that bond the veneers on their elastic moduli is negligible.

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EN 322:1999 Wood-based panels. Determination of moisture content

EN 323:1999 Wood-based panels. Determination of density

EN 827:2006 Adhesives. Determination of conventional solid content and constant mass solid

MODUŁY SPRĘŻYSTOŚCI FORNIRÓW W SKLEJCE SOSNOWEJ I BUKOWEJ

Streszczenie

Właściwości fornirów w arkuszu sklejki różnią się od ich właściwości w stanie początkowym, przed prasowaniem arkusza. Forniry w sklejce mają większą gęstość, co jest wynikiem ich sprasowania i przesycenia klejem. Znajomość właściwości sprężystych tych fornirów umożliwi analizę naprężeń i odkształceń w elementach konstrukcyjnych wykonanych ze sklejki, w tym stosowanie teorii układów warstwowych. W pracy przedstawiono wyniki badań dotyczących modułów sprężystości fornirów zawartych w sklejce sosnowej i bukowej. Obiektem badań były sklejki trzy- i pięciowarstwowe sklejone klejem mocznikowo- i fenolowo-formaldehydowym. W pierwszej części badań wyznaczono moduły sprężystości przy zginaniu pasm sklejek o osi podłużnej równoległej i prostopadłej do kierunku włókien w obłogach sklejki (rys. 1 i 2). Ich wartości przedstawiono w tabeli 2. Analiza wariancji wykazała, że moduły sprężystości przy zginaniu sklejki zależą od gatunku drewna sklejki, nie zależą natomiast od rodzaju użytego kleju (tabela 3). Na podstawie uśrednionych, dla sklejek z żywicą mocznikowo- i fenolowo-formaldehydową, wartości modułów sprężystości pasm sklejki, obliczono moduły sprężystości fornirów w sklejce: moduł w kierunku włókien i moduł w kierunku prostopadłym do włókien (tabela 4). Pominięto przy tym spoiny klejowe. Dla fornirów w sklejce pięciowarstwowej uzyskano nieco większe, o około 5%, moduły niż dla fornirów w sklejce trzywarstwowej. Moduły fornirów bukowych, zwłaszcza moduł w kierunku prostopadłym do włókien, są większe niż moduły fornirów sosnowych. Stopień anizotropii właściwości sprężystych forniru w jego płaszczyźnie, wyrażony jako stosunek modułu w kierunku włókien do modułu w kierunku prostopadłym do włókien, jest znacznie większy dla forniru sosnowego (około 26) niż dla forniru bukowego (około 16). Oszacowano błąd wynikający z pominięcia spoin klejowych przy wyprowadzeniu wzorów na moduły sprężystości forniru (tabela 5). Okazał się on mały.

Słowa kluczowe: fornir, sklejka, moduł sprężystości, drewno sosnowe, drewno bukowe