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ELASTIC PROPERTIES OF PARTICLEBOARD AS HETEROGENEOUS MATERIAL

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ABSTRACT

The investigations of elastic properties of the face and the core layer of particleboard are presented. The method of compressing the test specimens was employed. The electric resistance strain gauge technique was used to measure deformations of the test specimens. The board was treated as a plane isotropic material. The set of elastic constants, i.e. Young's moduli, Poisson's ratios and shear moduli were obtained. It was concluded that the particleboard layers are characterised by strong anisotropy of elastic properties.

Key words: particleboard, core layer, face layer, elastic properties, anisotropy

INTRODUCTION

A typical particleboard is a three-layer board which consists of a central layer (core) and two outer layers (faces). The structures of these layers differ significantly. The core layer, made of bigger chips with a lower resin content, is characterised by a lower compaction ratio and a higher porosity. As a result, this layer has a lower density and mechanical properties [6, 10, 11, 12].

Due to its technology, the particleboard, treated both as a monolith and in relation to its particular layers, is characterised by anisotropy of mechanical properties. Especially considerable differences occur between the directions parallel and perpendicular to the plane of the board. This affects the arrangement of the particles that during chip-spreading tend to fall with their longer dimension parallel to the plane of the board. Upon compression this arrangement becomes all the more clear. Therefore, the mechanical properties in the plane of the board depend mainly on the wood properties in the longitudinal direction, while those perpendicular to the plane of the board depend first of all on the wood properties in the radial and tangential directions.

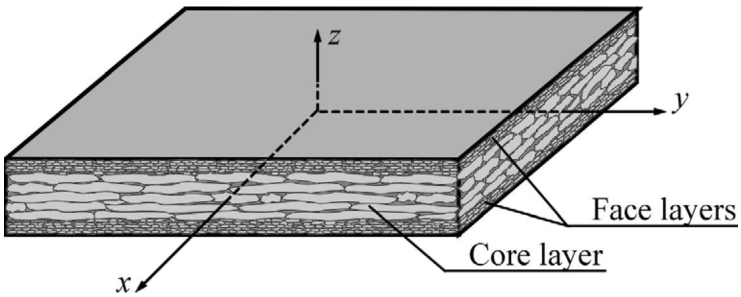
The knowledge of the mechanical properties of particleboard layers, in particular of their elastic properties, is important as it allows the application of bending theory of layered systems [2, 3, 5, 7, 9]. In addition, the elastic constants of particleboard layers are necessary for making analyses and simulations of constructions using numeric methods, including the most popular finite element method.

Unfortunately, the determination of the elastic constants of particleboard layers is complex and labour-consuming and, therefore, it is difficult to find them in the literature. The only known are the investigations of Keylwerth [5] and Kociszewski et al. [6], in which Young's modulus of particleboard layers was determined. Moreover Keylwerth [5] fixed shear modulus of these layers. Selected elastic constants were taken into account in these investigations, leaving their anisotropy out of consideration. That is why investigations were carried out to determine the set of elastic constants of a standard, commercial particleboard with the anisotropy of these properties taken into account.

THEORETICAL CONSIDERATIONS

The three-layer particleboard (Fig.1) can be regarded as an orthotropic body [2]. The principal axes of elasticity have the following directions: x –mat forming direction, y – perpendicular to the mat forming direction, and z – perpendicular to the board.

Fig. 1. Principal axes of the elasticity of three-layer particleboard



Hooke's law for the particleboard as an orthotropic material can most conveniently be written as a matrix equation:

$$\begin{bmatrix}\varepsilon_x\\ \varepsilon_y\\ \varepsilon_z\\ \gamma_{yz}\\ \gamma_{xz}\\ \gamma_{xy}\end{bmatrix}=\begin{bmatrix}S_{11} & S_{12} & S_{13} & 0 & 0 & 0\\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0\\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & S_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & S_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & S_{66}\end{bmatrix}\begin{bmatrix}\sigma_x\\ \sigma_y\\ \sigma_z\\ \tau_{yz}\\ \tau_{xz}\\ \tau_{xy}\end{bmatrix} \tag{1}$$

where

ε_x, ε_y,..., γ_{xy} = strain components,
σ_x, σ_y,..., τ_{xy}= stress components,
S_{11}, S_{12},..., S_{66} = compliance coefficients.

Substituting the compliance coefficients by the engineering elastic parameters, Hooke's law can be expressed in the following form:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \tag{2}$$

where

E_x, E_y, E_z = Young's moduli,
ν_{xy}, ν_{yx}, ν_{yz}, ν_{zy}, ν_{zx}, ν_{xz} = Poisson's ratios,
G_{yz}, G_{xz}, G_{xy} = shear moduli.

When analysing the arrangement of the particles in the plane of the board, one can note that they are orientated fairly randomly. As a result, elastic properties in the directions in this plane do not differ considerably from one another. Consequently, the plane of the particleboard can be roughly regarded as the plane of isotropy, and the board as a plane isotropic material [1, 2, 6, 8].

This plane isotropy requires that:

$$E_x = E_y \;, \quad \nu_{xy} = \nu_{yx} \;, \; \nu_{yz} = \nu_{xz} \;, \; \nu_{zy} = \nu_{zx} \;, \quad G_{yz} = G_{xz} \tag{3}$$

Therefore, Hooke's law for the particleboard as a plane isotropic material can be written in the form:

$$\begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{yz} \\ \gamma_{xz} \\ \gamma_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{xy}}{E_x} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_x} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{xz}}{E_x} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{yz} \\ \tau_{xz} \\ \tau_{xy} \end{bmatrix} \tag{4}$$

As it follows from the above, the elastic properties of plane isotropic body are described by seven constants: 2 Young's moduli, 3 Poisson's ratios and 2 shear moduli.

Considering the relation $S_{ij} = S_{ji}$ we obtain the following relationship:

$$\frac{\nu_{xz}}{E_x} = \frac{\nu_{zx}}{E_z} \tag{5}$$

therefore

$$\nu_{zx} = \frac{E_z}{E_x}\nu_{xz} \tag{6}$$

Additionally, the known relationship between the elasticity constants occurs in the isotropic plane of the board:

$$G_{xy} = \frac{E_x}{2(1+\nu_{xy})} \tag{7}$$

It follows that at least five constants are required to describe the particleboard as a plane isotropic body:

E_x = Young's modulus parallel to the board plane,
E_z = Young's modulus in perpendicular direction to the board plane,
G_{xz} = shear modulus in the transversal plane of the board,
ν_{xy} = Poisson's ratio in the board plane,
ν_{xz} = Poisson's ratio in the transversal plane of the board.

In order to experimentally determine some of the elastic constants of the material, it is useful to consider the compliance coefficients S'_{ij} in the x', y', z' system, which is rotated in relation to the principal axes of elasticity. These coefficients are related to the coefficients S_{ij} with appropriate relations described by Keylwerth [4]. Particularly for the system of axes rotated by an angle of 45° around the *y* axis there is a very simple relationship:

$$2\left(S_{11}^{*} - S_{13}^{*}\right) = S_{55} \tag{8}$$

where

S_{11}^{*} and S_{13}^{*} = compliance coefficients related to the system of axes rotated by an angle of 45° around the *y* axis,

S_{55} = compliance coefficient related to the principle *x*, *y*, *z* axes of elasticity.

Considering the following relationships between compliance coefficients and engineering elastic parameters:

$$S_{11}^{*} = \frac{1}{E_x^{*}} \quad , \quad S_{13}^{*} = -\frac{\nu_{zx}^{*}}{E_z^{*}} \quad , \quad S_{55} = \frac{1}{G_{xz}} \tag{9}$$

we obtain a formula in the known form:

$$G_{xz} = \frac{E_x^{*}}{2\left(1+\nu_{zx}^{*}\right)} \tag{10}$$

where:

E_x^{*} = Young's modulus for the direction in the *xz* plane, forming the angle of 45° to the *x* axis,

ν_{zx}^{*} = Poisson's ratio relating passive and active strains for two mutually perpendicular directions in the *xz* plane and forming angles of 45° to the *x* and *z* axis.

G_{xz} = shear moduli in the *xz* plane.

Equation (10) permits the calculation of the shear modulus G_{xz} through experimental determination of E_x^* i ν_{zx}^* parameters.

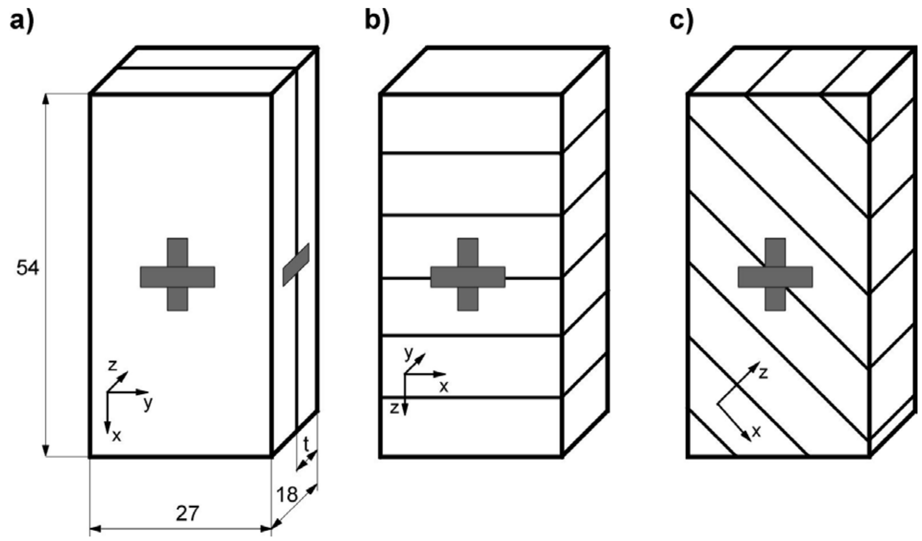
Presented theoretical considerations concern the particleboard as a monolithic material. They can be also referred to its layers, both face and core ones.

MATERIALS AND METHODS

The experiment was carried out for a typical commercial three-layer particleboard with the thickness of 18 mm, medium density of 695 kg/m^3, and moisture content of 8%. The 9 mm strips from the core layer and the 2.5 mm strips from the face layer were separated from the board. The densities determined for the face and core layers averaged 851 and 541 kg/m^3 respectively.

For determining the elastic constants, the method of compressing the test specimens and measuring their elastic strains was employed. Three types of test specimens were used: the longitudinal (Fig. 2 a) with the longest side parallel to the board plane, the transverse (Fig. 2 b) for which this side was perpendicular to the board plane, and the diagonal (Fig. 2 c) for which the angle between the planes of the board and the relevant sides of the specimen was equal to 45^o.

Fig. 2. Test specimens for the determination of the elastic constants of the particleboard layers together with strain gages glued onto the visible and opposite sides of the specimens: a) longitudinal specimen, b) transverse specimen, c) diagonal specimen; t – layer thickness



The test specimens were prepared by gluing an appropriate number of strips into assemblies and cutting cuboids with the dimensions 27 x 18 x 54 mm from them. Five test specimens of each type were prepared.

The electric resistance strain gage technique was used to measure elastic strains. The strain gages with the nominal resistance of 120 Ω, measurement bases of 10 or 20 mm and gage factor equal to 2.15 were glued onto the specimens (Fig. 2). They were placed symmetrically on the opposite sides of the specimens and serially connected to the Wheatstone bridge that allowed measuring strains with an accuracy of 1 μS. The increment of the longitudinal and lateral strain due to the increase on compression force from F_1 to F_2 were measured. The force F_2 was about 20% of the mean value of the failure force for a given type of test specimen and a given layer of particleboard. The force F_1 was equal to ¼ of the force F_2 (Table 1).

Table 1. Values of compression force

Type of test specimen	Core layer specimen		Face layer specimen	
	F_1 [N]	F_2 [N]	F_1 [N]	F_2 [N]
Longitudinal	50	200	250	1000
Transverse	7.5	30	20	80
Diagonal	10	40	20	80

As a result of the investigations of the longitudinal specimens, the elastic constants E_x, ν_{xy} and ν_{xz} were calculated:

$$E_x = \frac{\Delta F}{ab\,\Delta\varepsilon_x} \quad , \quad \nu_{xy} = \left|\frac{\Delta\varepsilon_y}{\Delta\varepsilon_x}\right| \quad , \quad \nu_{xz} = \left|\frac{\Delta\varepsilon_z}{\Delta\varepsilon_x}\right| \tag{11}$$

where

a and b = dimensions of specimen cross-section,
$\Delta\varepsilon_x$ = increment of the longitudinal strain corresponding to the increment $\Delta F = F_2 - F_1$
$\Delta\varepsilon_y$ and $\Delta\varepsilon_z$ = increment of the lateral strain in the y and z direction, respectively.

The shear modulus G_{xy} was calculated directly from the equation (7).

The deformations of the transverse specimens allowed the constants E_z and ν_{zx} to be calculated:

$$E_z = \frac{\Delta F}{ab\,\Delta\varepsilon_z} \quad , \quad \nu_{zx} = \left|\frac{\Delta\varepsilon_x}{\Delta\varepsilon_z}\right| \tag{12}$$

where

$\Delta\varepsilon_z$ = increment of the longitudinal strain corresponding to the increment ΔF,
$\Delta\varepsilon_x$ = increment of the lateral strain in the x direction.

Based on the investigations of the diagonal specimens the constants E_x^* and ν_{xz}^* were calculated:

$$E_x^* = \frac{\Delta F}{ab\,\Delta\varepsilon_1} \quad , \quad \nu_{xz}^* = \frac{\Delta\varepsilon_2}{\Delta\varepsilon_1} \tag{13}$$

where

$\Delta\varepsilon_1$ = increment of the longitudinal strain due to the increment ΔF,
$\Delta\varepsilon_2$ = increment of the lateral strain due to the increment ΔF,

and then the shear modulus G_{xz} according to the equation (10).

As it was mentioned earlier, at least 5 elastic constants should be defined to describe the board as a plane isotropic material. In spite of that, 6 constants were experimentally defined, which allowed an additional verification of the results.

ANALYSIS OF RESULTS

The results of the investigations – the mean values and standard deviations for elastic constants of the examined layers of the particleboard are shown in Table 2.

The particleboard layers are characterised by strong anisotropy of elastic properties. In order to determine the rate of this anisotropy, the values of elasticity moduli were compared (Table 3). The rate of anisotropy expressed as the ratio of Young's modulus E_x in the direction tangential to the layer to Young's modulus E_z in the direction perpendicular to the layer, is very high – it amounts to 9.6 for the face and 8.1 for the core layer. The rate of anisotropy expressed as the ratio of the shear modulus G_{xy} in the plane tangential to the layer to the shear modulus G_{xz} in the plane perpendicular to the layer, is lower – it amounts to 3.5 for the face, and 4.0 for the core layer (Table 3).

Table 2. Elastic constants of the layers of the tested particleboard

Elastic property		Face layer		Core layer	
		mean value	standard deviation	mean value	standard deviation
Young's moduli [MPa]	E_x E_z	3830 400	473 22.4	1450 180	106 8.4
Poisson's ratios	ν_{xy} ν_{xz} ν_{zx}	0.28 0.36 0.035	0.051 0.036 0.007	0.26 0.33 0.047	0.044 0.068 0.009
Shear moduli [MPa]	G_{xy} G_{xz}	1496 430	- 46.2	575 145	- 13.1

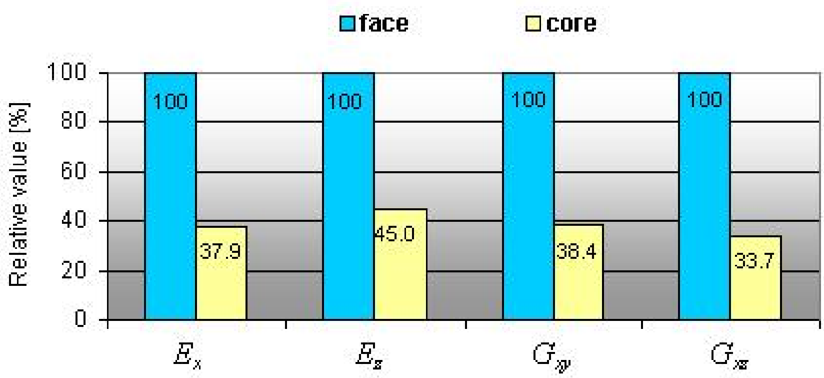
Table 3. Comparison of moduli of elasticity

Compared moduli	Face layer	Core layer
E_x/E_z ratio	9.6	8.1
G_{xy}/G_{xz} ratio	3.5	4.0

Poisson's ratio ν_{xz} related to the transverse plane achieves a greater value (by about 28%) both for the face and for the core layer than Poisson's ratio ν_{xy} related to the layer plane. The enormous difference between the values of the ratios ν_{xz} and ν_{zx} results from the difference between the values of Young's moduli E_x and E_z (Table 2).

The next comparison of elastic properties is between the face and the core layer (Fig. 3). The values of the moduli of elasticity of the face layer were assumed to be the basis of this comparison. The moduli of elasticity of the core layer are much smaller and range from 33.7 to 45.0% of the moduli of the face layer. The smallest difference (55%) is exhibited by Young's modulus E_z in the direction perpendicular to the layer. The moduli of elasticity of the core layer are on average 2.6 times smaller than the moduli of the face layer. The medium densities of the core and face layer were 851 and 541 kg/m^3 respectively. The density of the core layer was 1.6 times smaller. One can state that the relative difference between the elastic moduli of the core and the face layer is greater than the relative difference in the density. Similar proportions for particleboards with different thickness were found by Dueholm (1976).

Fig. 3. Comparison of the moduli of elasticity of the face and core layer



For both Poisson's ratios ν_{xy} and ν_{xz} the differences for the core and face layer are rather small. These ratios for the core layer are a few percent smaller. A greater difference concerns Poisson's ratio ν_{zx} , which is 34.3% greater for the core layer (Table 2).

Six elastic constants, including Young's moduli E_x and E_z and Poisson's ratios ν_{xz} and ν_{zx}, were directly determined by measuring relevant deformations of the test specimens. These constants should satisfy the equation (5). The values of ratios for this equation for both layers are given in Table 4. These values are not exactly the same for a given layer, however, their relative differences do not exceed the limit of 10%. This approximate satisfaction of the equation (5) is a positive verification of the assumed model of anisotropy of elastic properties of particleboard layers.

Table 4. Comparison of the ratios of Poisson's ratio to Young's modulus

Layer	$\frac{\nu_{xz}}{E_x}\left[\frac{mm^2}{N}\right]$	$\frac{\nu_{zx}}{E_z}\left[\frac{mm^2}{N}\right]$	Relative difference [%]
Face	9.40 x 10^{-5}	8.75 x 10^{-5}	-6.9
Core	2.28 x 10^{-4}	2.50 x 10^{-4}	9.6

To end with, let us evaluate the employed method of determining elastic constants, consisting in compressing the test specimens and measuring their strains by means of electric resistance strain gages. This method is labour-consuming, the preparation of diagonal specimens being especially laborious. However, it has turned out to be useful, its main advantage being the possibility to determine a set of elastic constants, i.e. Young's moduli, Poisson's ratios and shear moduli.

CONCLUSIONS

The investigations carried out make it possible to draw the following conclusions:

1. The particleboard layers: the face and the core layer, are characterised by strong anisotropy of elastic properties. Young's modulus in the direction tangential to the layer is several times greater than that in the perpendicular direction.
2. Moduli of elasticity of the face and the core layer differ substantially and for the core are on the average 2.6 times smaller than for the face layer.
3. The relative differences between the elastic moduli of layers are greater than the relative difference between their densities.

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