WOOD RESEARCH
51 (1): 2006
1-10

PLYWOOD STRESS OPTIMISATION USING THE FINITE ELEMENT METHOD

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ABSTRACT

In this paper, relevant stress and strain components are investigated with the aim to optimise a construction of veneer plywood under a bending load. For this purpose a veneer beech plywood of 13 plies is laboratory-made and its bending properties are measured. The laboratory results are used as the basic values for creating 2D models, which are used then for optimisation and analyses using the finite element method, depending of the thickness variations of outer plies. The obtained results indicate different relations of stress and strain distribution due to different type of plywood structure constructions and its grain directions. When the veneer thickness of the outer plies is increased, the values of Von Mises stress decreases according to different relation forms. It has a second-order polynomial form when the grain direction is parallel, but it has a third-order polynomial form when the grain direction is perpendicular to the load direction. As a difference of stress relations where both relations have decreasing form, the values of equivalent strains has the opposite relation form. A strain relation form decreases only if the grain direction is parallel, but it increases if the grain direction is perpendicular to the load direction.

KEY WORDS: plywood, optimisation, stress, strain, finite element method

INTRODUCTION

The optimisation of plywood mechanical properties can be achieved by using different construction solutions, either using only veneers as structural material, or combining it with different types of non-wood materials. In the previous research, the analysis of plywood mechanical properties and its combination with different types of synthetic carbon fibres is done. Presented is a wide variety of stress distribution influenced by the used materials with very different mechanical properties (Brezović et al. 2003). The carbon fibres had had a large influence on stress variation independently of their position in the plywood composition. In the further research, the influence of wood species with high and low mechanical properties, on the optimisation of heterogeneous plywood is studied. Heterogeneous plywood had been constituted of different veneer and glass fibre plies, and it has been concluded that variations in stress distribution were smaller in correlation with the difference between the mechanical properties of used materials (Kljak et al. 2003). If the optimisation is based only on the same materials' species e.g. homogenous plywood, than the major emphasis should be taken on analysing and optimisation of critical plies with maximal stress.

In the aim of making plywood optimisation, a mathematical model was developed which enables the determination of elastic properties of veneer plywood according to given orthotropic properties of each layer, and plywood's construction (Gerrard et al. 1987). After that, a theoretical model for predicting plywood bending properties according to its construction and mechanical properties of each plies is developed (Booth et al. 1990). However, plywood optimisation depending on relevant stress and strain values, especially in a critical plies, is not sufficiently researched. So, the aim of this paper is to find the relation between stress and strain components depending on construction variability of plywood outer plies.

MATERIAL AND METHODS

Multi-ply beech plywood, with symmetrical construction and cross ply orientation, are laboratory made. All the plies of rotary cut veneer are classified at I class according to the norm HRN EN 635-2. A carbamid-formaldehyde resin LENDUR 120 („Nafta" Lendava) was used. The applied resin content was 210 g/m^2, the pressing temperature 120 ˚C, specific pressure 1.6 N/mm^2, and pressing time 13 min. Laboratory- made panels have had a nominal thickness of 18.2 mm, consisting of 13 plies with each of them being 1.4 mm thick. A procedure of cutting test pieces and measuring bending properties was done according to norm HRN EN 310. Bonding quality was measured according to norm HRN EN 314 and the requirements for Class 1 fulfilled. Plywood density was 754.92 kg/m^3 according to norm HRN EN 323, and moisture content was 7.5% according to norm HRN EN 322.

A software COSMOS/M 2.6 with module GEOSTAR and SHELL4L element was used for the analysis using the finite element method (FEM). Veneer plies are defined as anisotropic material and values of specific constants were as follows: Modulus of elasticity EX=13700 N/mm^2, EY=1140 N/mm^2, EZ=2240 N/mm^2; modulus of rigidity GXY=1060 N/mm^2, GYZ=460 N/mm^2, GXZ=1610 N/mm^2, and Poisson numbers NUXY=0.51, NUYZ=0.36, NUXZ=0.45 (Dinwoodie et al. 1981). The directions of Cartesian co-ordinate axes x, y, and z coincide with principal wood directions L (longitudinal), T (tangential) and, R (radial), respectively.

As the optimisation was based on a 2D model, actually by the SHELL4L element, the relation between stress and strain was defined by nine elastic components according to term (1). In the plywood optimisation process the temperature effect was not considered.

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \\ \tau_{yz} \\ \tau_{zx} \end{Bmatrix} = \begin{bmatrix} E_{11} & E_{12} & E_{14} & 0 & 0 \\ E_{12} & E_{22} & E_{24} & 0 & 0 \\ E_{14} & E_{24} & E_{44} & 0 & 0 \\ 0 & 0 & 0 & E_{55} & E_{56} \\ 0 & 0 & 0 & E_{56} & E_{66} \end{bmatrix} \left(\begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \\ \gamma_{yz} \\ \gamma_{zx} \end{Bmatrix} - (T - T_0) \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_4 \\ \alpha_5 \\ \alpha_6 \end{Bmatrix} \right) \tag{1}$$

The results obtained by the laboratory measurements were used as a base for a FEM model creating. The geometry of the testing model and the position of loading points were also created according to the laboratory-measuring scheme. In a meshing process, a total of 272 finite elements were defined on the testing model (Fig. 1).

Since the laboratory-measured veneer thickness was 1.4 mm for each of the plies, the results coming from testing panels with such a structure are considered as a basic values. In the FEM model, the veneer thickness of outer plies was varying in a rage from 0.6 to 3.0 mm, in harmony with norm HRN EN 635-4. So the total number of analysing models was six, each with a different veneer thickness of outer plies increasing by 0.6 mm as follows: 0.6; 1.2; (1.4); 1.8; 2.4, and 3.0 mm.

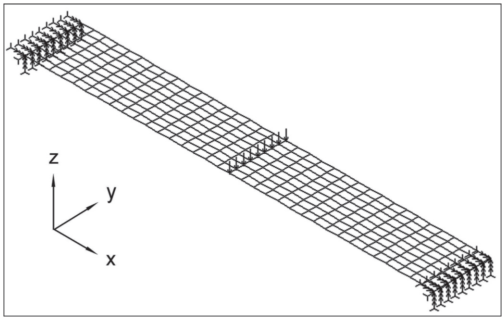

Fig. 1: FE modelling

RESULTS AND DISCUSSION

The results of bending properties obtained by laboratory measuring are presented in the Table 1. It can be seen that the values of elastic modulus for bending strength are nearly the same in the direction parallel (9924 N/mm^2) and perpendicular to the grain (9333 N/mm^2), as a sequence of multilayer plywood construction. A similar relation could be seen in bending strength, too. During the determination of elastic modulus, a mean value of maximal force was 2767 N parallel, and it was 2684 N perpendicular to the grain. Based on the experimental values, the analysis of stress components using the finite element method is carried out. All plies were included in the analysis and the values of stress and strain in the outer plies are shown as critical elements. The distribution of normal stress SX in the outer ply, is shown in Figure 2, and the shear stress TXY in the same ply is shown in Figure 3. It is seen that normal stress has a maximum value in the centre of test piece, while maximum shear stress is distributed along the plywood edges.

As opposed to real model simulation, a simulation model for plywood construction optimisation has a force value of 2767 N in a both directions, in the aim to reduce the force to a constant value in the analyses of the process of stress and strain components. The values of Von Misess stress, in a case when the grain direction is parallel with the load direction, is shown in Figure 4. (The term grain direction is used only for the grain direction of the outer plies of plywood). It is clearly seen that the thickness increase of the outer veneer has an influence on stress decreasing, while the trend line has the form of a second-order polynomial with a high degree of correlation, practically R=1. In the case when the load has a direction perpendicular to the grain, the thickness increase of outer veneer has an influence on stress decreasing too, but the trend line has a form of a third-order polynomial (Fig. 5). In the central part of the trend line there is a presence of stress decreasing stagnation as a consequence of a certain shear stress increase (TYZ) while all other components continuously decrease (Tab. 2).

Tab. 1: Experimental results of bending properties

Modulus of elasticity					
	n	Arithmetic mean (N/mm^2)	Standard deviation (N/mm^2)	Coefficient of variation	Deflection (mm)
Parallel	24	9924.287	1366.320	0.138	14.10
Perpendicular	24	9333.308	1023.109	0.110	15.79
Bending strength					
	n	Arithmetic mean (N/mm^2)	Standard deviation (N/mm^2)	Coefficient of variation	Deflection (mm)
Parallel	24	92.347	14.922	0.162	14.10
Perpendicular	24	89.450	11.178	0.125	15.79

*n – number of test pieces

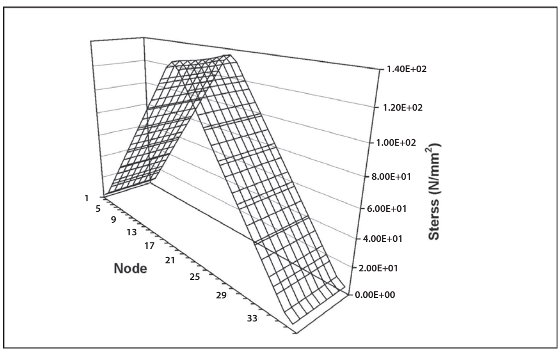

Fig. 2: Distribution of normal stress in the X direction

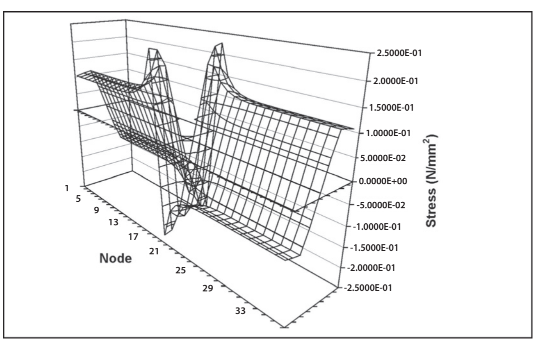

Fig. 3: Distribution of shear stress in the X-Y plane

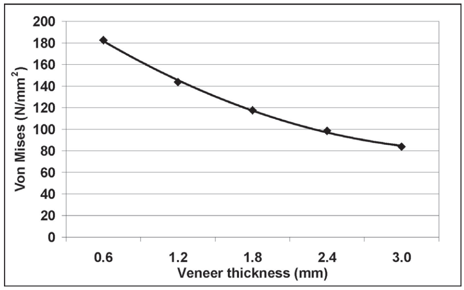

Fig. 4: Von Mises stress parallel to the grain direction

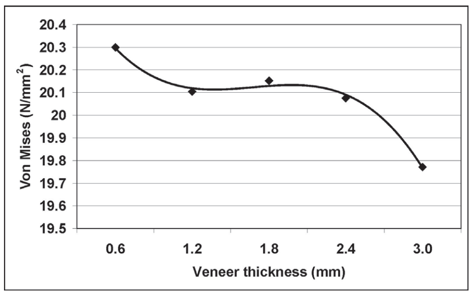

Fig. 5: Von Mises stress perpendicular to the grain direction

Tab. 2: Relevant components of maximum Von Mises stress

Stress components – perpendicular (N/mm^2)					
Veneer thickness (mm)	SX	SY	TXY	TXZ	TYZ
0.6	1.75E+01	-8.88E+00	1.27E-07	-3.87E-07	1.70E-01
1.2	1.74E+01	-6.87E+00	1.75E-07	-3.87E-07	1.79E-01
1.8	1.68E+01	-5.57E+00	2.05E-07	-3.73E-07	1.82E-01
2.4	1.58E+01	-4.63E+00	2.24E-07	-3.28E-07	1.81E-01
3.0	1.43E+01	-3.91E+00	2.25E-07	-3.28E-07	1.79E-01
Stress components - parallel (N/mm^2)					
Veneer thickness (mm)	SX	SY	TXY	TXZ	TYZ
0.6	1.86E+02	6.57E+00	5.96E-08	-1.37E-06	2.08E-01
1.2	1.46E+02	4.96E+00	6.33E-08	-1.31E-06	1.98E-01
1.8	1.20E+02	3.89E+00	5.96E-08	-1.13E-06	1.89E-01
2.4	1.00E+02	3.11E+00	5.22E-08	-1.10E-06	1.81E-01
3.0	8.52E+01	2.52E+00	5.96E-08	-9.54E-07	1.73E-01

SX, SY – normal stress in the x-, y- direction, respectively.
TXY, TXZ, TYZ – shear stress in the x-y, x-z, y-z plane, respectively.

Except for the different relations in the Von Mises stress decrease, it is interesting to note an opposite trend in strain variability depending of the thickness variability of outer veneer plies. When the load direction is parallel with the grain direction, with the veneer thickness increasing the equivalent strains decreasing, the relation has a form of second-order polynomial (Fig. 6). As opposed to this, when the load direction is perpendicular to the grain direction, with the veneer thickness increasing, the equivalent strains increase as well (Fig. 7). This relation could be explained by the results of relevant strain components analyses, where it can be seen that the increase of equivalent strain values is a consequence of the increase of normal strain in X direction, while the strain values of all other components decrease. In the case of the load direction being parallel with the grain direction, all components of equivalent strain increase proportionally (Tab. 3).

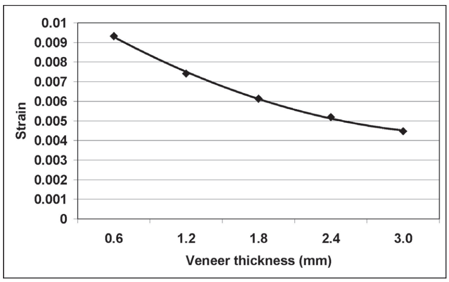

Fig. 6: Equivalent strain parallel to the grain direction

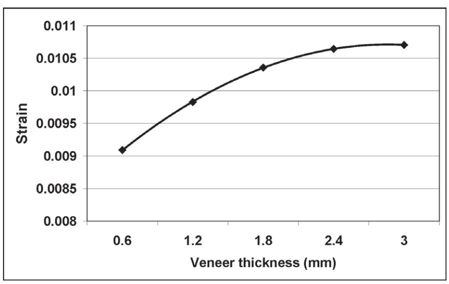

Fig. 7: Equivalent strain perpendicular to the grain direction

The increase of strain in direction X, is a direct consequence of a small influence of thickness increase of outer veneer as well as total plywood construction, on a displacement value decrease. This is due to low mechanical properties in tangential direction, (Fig. 8). This problem is not present if the outer plies of veneer are parallel with load direction, when displacement values decrease more progressive due to veneer thickness increasing (Fig. 9).

Tab. 3: Relevant components of maximum equivalent strains

Strain components – parallel					
Veneer thickness (mm)	EPSX	EPSY	GMXY	GMXZ	GMYZ
0.6	1.33E-02	-1.06E-03	2.46E-04	-1.96E-03	3.39E-04
1.2	1.05E-02	-1.00E-03	2.21E-04	-1.77E-03	3.25E-04
1.8	8.57E-03	-9.54E-04	2.02E-04	-1.61E-03	3.13E-04
2.4	7.18E-03	-9.15E-04	1.85E-04	-1.48E-03	3.02E-04
3.0	6.11E-03	-8.78E-04	1.71E-04	-1.36E-03	2.91E-04
Strain components – perpendicular					
Veneer thickness (mm)	EPSX	EPSY	GMXY	GMXZ	GMYZ
0.6	1.30E-02	-1.06E-03	2.46E-04	-1.94E-03	3.41E-04
1.2	1.41E-02	-9.87E-04	2.11E-04	-1.86E-03	3.14E-04
1.8	1.50E-02	-9.43E-04	1.85E-04	-1.79E-03	2.90E-04
2.4	1.54E-02	-9.06E-04	1.64E-04	-1.73E-03	2.69E-04
3.0	1.55E-02	-8.68E-04	1.48E-04	-1.68E-03	2.51E-04

EPSX, EPSY, EPSZ – Average element strain in the X-, Y-, Z-direction, respectively.
GMXY, GMYZ, GMZX, - Element shear strain in the X-Y, Y-Z, Z-X plane, respectively.

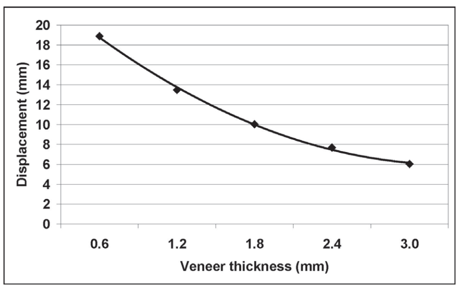

Fig. 8: Plywood displacement parallel to the grain direction

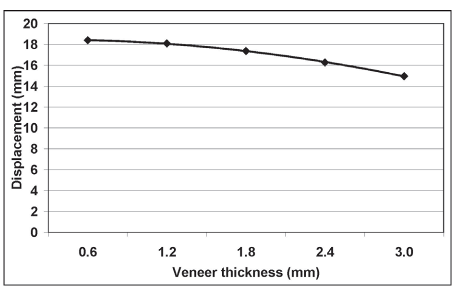

Fig. 9: Plywood displacement perpendicular to the grain direction

In the basic model, Von Mises stress was perpendicular to the grain was 19.529 N/mm^2, while the minimal stress of reference model was 19.771 N/mm^2. This means that the mechanical properties of veneer ply, in tangential direction, could not carry the same amount of stress as it could carry in longitudinal direction notwithstanding of its double thickness increase. In the case of strains, the maximum equivalent strain in the basic model was 0.00976, while the strain values of reference models was increased by veneer thickness growth and the maximal value was 0.01071.

Consideration such different trends of stress and strain, it is obvious that for the design of plywood structure the dimensioning an outer plies of panel has a great impact, it being based on analysis of relevant components of material inner stress.

CONCLUSIONS

Based on the results obtained by 2-D simulation model and experimental results of multilayer beech plywood the following conclusion could be made:

1. Under the bending loads, with outer ply thickness increase different stress relations occur depending on grain direction. When the load direction is parallel with the grain direction, the relation has a form of second-order polynomial, but when it is perpendicular to grain direction the relation takes up the form of third order polynomial, as a consequence of a partial shear stress increase.
2. With the veneer thickness increasing, opposite strain relations occur. When the load direction is parallel to the grain, the amount of equivalent strain decreases with the thickness increase, but when the load direction is perpendicular to the grain, the amount of equivalent strain increases as a consequence of normal strain increase.
3. With the increase of the thickness of outer plies, displacement values decrease with different intensities. The displacement values decrease more depending on whether the grain direction is parallel with the load direction as a consequence of anis tropic properties of veneer plies.

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