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INFLUENCE OF PLYWOOD STRUCTURE ON SANDWICH PANEL PROPERTIES: VARIABILITY OF VENEER THICKNESS RATIO

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ABSTRACT

In this study, a 3-D analysis of sandwich-structured composite plywood was done, in the aim to determine a stress and strain distribution in their individual layers. The influence of veneer thickness ratio in plywood on bending properties of sandwich panel was observed. The sandwich panel has been made from 3-layer beech veneer plywood (t_{nom} = 4.5 mm) and PVC foam core (t_{nom} = 20 mm). The experimental results contain the flexural properties of the sandwich panel, obtained by the three-point bending test method. Analysis of stress and strain distribution is carried out using the finite element method.

The research results indicate that the variation of veneer thickness ratio in plywood significantly changes the stress distribution in each layer of the sandwich panel. A significant ratio of normal and shear stress in the transverse direction was determined in each layer of plywood, as well as in the core, which suggests the importance of their consideration in the analysis of sandwich panels.

KEY WORDS: plywood, sandwich-panel, bending properties, finite element method.

INTRODUCTION

In a typical analysis of the mechanical properties of sandwich panel, its faces are often considered as monolithic material with homogenous properties. If the plywood is used as a face material, then such consideration is not adequate from the aspect of stress distribution. This is because plywood has a laminated structure and its properties are not homogenous in a cross-section (Kollman et al. 1975). The results of previous research, based on 2D FEM analysis of plywood, show a strong influence of veneer thickness of outer veneer on stress and strain trend lines (Kljak et al. 2006). Also, several studies indicated the significant influence of mechanical properties of plywood changing the mechanical properties of the sandwich panel (Kawasaki et al. 1999 and 2003, Hu et al. 2005). Based on this we can assume that stress in the individual layers of sandwich panel will be significantly different by the influence of a different plywood structures. Therefore it has been necessary to research the influence of veneer thickness ratio in plywood on the stress distribution in all layers of the sandwich panel, under the bending load. An analysis of the distribution of stress and strain was carried out in the 3D system using the finite element method.

MATERIAL AND METHODS

Experimental work

The experimental work has been divided into two phases. In the first phase, beech veneer plywood was made using the tact pressing process. In the second phase sandwich panels were made by bonding these veneer plywoods onto the PVC foam core, also using the tact pressing process. All plywoods were constructed as three-layer veneer plywood with a constant thickness of 4.5 mm, but with different veneer thickness ratios. All plywoods had a cross-aligned veneer plies. The veneer thicknesses were 0.5, 1.5, 2.5, 3.5 mm, according to the norm HRN EN 635. For the plywood manufacturing carbamide-formaldehyde resin LENDUR 120 (Nafta-Petrochem d.o.o.) was used. The technological parameters of pressing the beech plywood were: applied resin content was: 200 g/m^2, pressing temperature: 120°C, specific pressure: 1.6 N/mm^2, pressing time: 7 min., veneer moisture content: 6.4%.

In the second phase experimental sandwich panels with plywood faces and a rigid PVC core were built. The core of the sandwich-structure composite was considered a constant size and was made from rigid expanded PVC (HEREX C70.75, Alcan Airex AG) with a thickness of 20 mm. Considering that the sandwich panel faces were made of plywood and that the core was made of expanded PVC, its structure and symbols are shown in Tab. 1.

Tab. 1: Symbols and structure of the sandwich panel

Symbol	Sandwich panel structure	Legend
SP0	$[0_{1,5}/0_{1,5}/0_{1,5}/0_{20}/0_{1,5}/0_{1,5}/0_{1,5}]_T$	$[\theta_{t1}/\theta_{t2}/\theta_{t3}/\theta_{t4}/\ \theta_{t3}/\theta_{t2}/\theta_{t1}]_T$
SP0.5	$[0_{2,0}/90_{0,5}/0_{2,0}/0_{20}/0_{2,0}/90_{0,5}/0_{2,0}]_T$	
SP1.5	$[0_{1,5}/90_{1,5}/0_{1,5}/0_{20}/0_{1,5}/90_{1,5}/0_{1,5}]_T$	θ – layer angel (°)
SP2.5	$[0_{1,0}/90_{2,5}/0_{1,0}/0_{20}/0_{1,0}/90_{2,5}/0_{1,0}]_T$	t – layer thickness (mm)
SP3.5	$[0_{0,5}/90_{3,5}/0_{0,5}/0_{20}/0_{0,5}/90_{3,5}/0_{0,5}]_T$	T – total thickness

A polyurethane resin KLEIBERIT PUR-LEIM 501 (KLEBCHEMIE M. G. Becker + Co. KG) was used for bonding the veneer plywood onto the PVC foam core. The technological parameters for pressing the sandwich panel were: applied resin content: 180 g/m^2, pressing temperature: 50°C, specific pressure: 0.8 N/mm^2, pressing time: 20 min.

The experimental panels were made with the dimensions 500x500 mm, after which they were conditioned under standard conditions of relative humidity of 65 ± 5% and a temperature of 20 ± 2%. Following panel conditioning, the relevant mechanical and physical properties were determined according to official norms. Bending properties of the sandwich panels were determined according to the norm ASTM C 393-00, on the short beam, single-point load, midspan loading (Fig. 1).

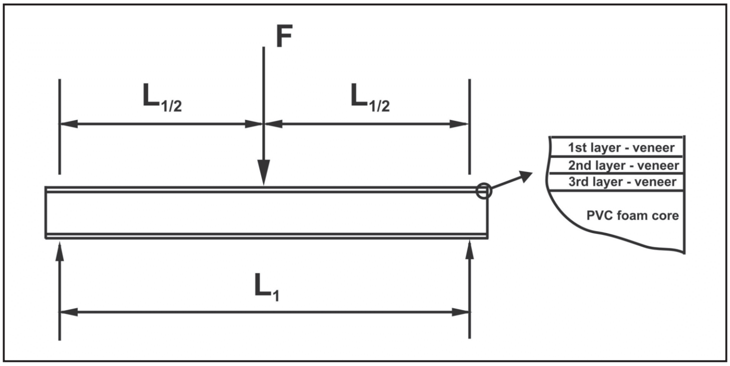

Fig. 1: Schematic representation of the loading points according to ASTM C 393-00 and the structure of the sandwich panel

FEM simulations

The FEM (finite element method) modelling of sandwich panels and calculations of its relevant properties were obtained using the software packet Cosmos/M 2.6. A linear structural composite 3D 8-node solid element was selected as the basic element.

The boundary conditions, the load directions and the dimensions of simulated sandwich panel test pieces were created according to the real laboratory testing procedure. For all FEM models the applied load had a constant value that was based on experimental results. This load has been calculated from the fifth percentile of bending strength for the sandwich panels SP1.5, parallel to the grain direction. All types of sandwich panel structures, with different veneer thickness ratio and load directions (parallel and perpendicular), were created as FEM models.

Prior to setting up the model in the Cartesian coordinates system, the main axes were coincided with the main directions of wood strength as follows: the longitudinal direction with the x axis, the tangential direction with the y axis and the radial direction with the z axis.

The elastic properties of the structural materials were based on literature data. Modulus of elasticity for a beech wood were: EX=13700 N/mm^2, EY=1140 N/mm^2, EZ=2240 N/mm^2; modulus of rigidity GXY=1060 N/mm^2, GUZ=460 N/mm^2, GXZ=1610 N/mm^2 and Poisson's ratio NUXY=0.51, NUYZ=0.36, NUXZ=0.45 (Dinwoodie, et al. 1981). The cross-linked PVC foam core has nearly isotropic properties (Viana, et al. 2002). The elastic properties of PVC foam were based on manufacturer's technical data: modulus of elasticity 83 N/mm^2, modulus of rigidity 30 N/mm^2 and Poisson's ratio 0.3 N/mm^2.

RESULTS AND DISCUSSION

The experimental results include the results of relevant properties of the sandwich panels. All veneers were classified by surface appearance into Class I, according to the HRN EN 635. Plywood moisture content was 8.6, according to the HRN EN 322. Sandwich panel density was 327.544 kg/m^3, according to the HRN EN 323. Bending properties of the sandwich panel were determined according to norm ASTM C 393-00. The obtained results indicate the grate influence of different sandwich structures (plywood structures) on the stress value in the faces and the core (Tab. 2).

Tab. 2: Bending properties of sandwich panels

	τ_c N/mm^2	σ_f N/mm^2	*D* N-mm^2	*U* N	*Δ* mm
Parallel					
SP0	1.559	33.410	865580954.6	47216.4	4.30
SP0.5	1.433	30.709	977692674.3	50622.7	4.02
SP1.5	1.155	24.746	658627820.0	43910.2	3.20
SP2.5	1.222	26.193	961013787.9	51715.2	3.46
SP3.5	0.983	21.055	538377165.8	48819.8	2.98
Perpendicular					
SP0	0.394	8.435	48342916.0	48130.1	3.52
SP0.5	0.788	16.884	57431254.9	47941.8	6.22
SP1.5	0.724	15.523	63225457.4	43606.8	4.86
SP2.5	1.039	22.257	300116111.2	50120.3	3.70
SP3.5	1.010	21.653	539819684.6	48919.3	3.07
τ_c – core shear stress; σ_f – facing bending stress; D – panel bending stiffness; U – panel shear rigidity; Δ – total beam midspan deflection					

The 3D numerical simulation was conducted in order to obtain an answer to questions of the stress and strain distribution in each layer of plywood and in the core. It was not possible to achieve the answer based only on experimental results, because in the standard testing method the three-layer plywood is considered to be a monolithic homogenous material. Therefore the analysis was conducted using the Von Mises stress and equivalent strain, as well as its components. Fig. 2 shows the distribution of Von Mises stress in PVC foam core of sandwich panel SP1.5.

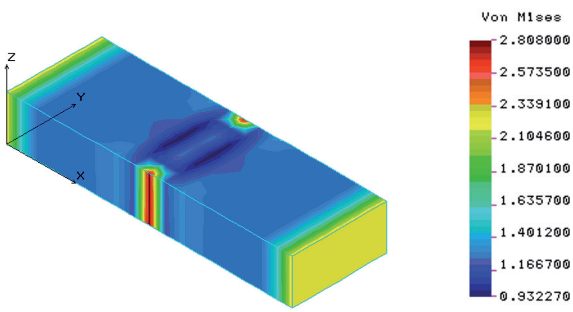

Fig. 2: Distribution of Von Mises stress in the PVC core, for the sandwich panel model SP1.5

The distribution of Von Mises stress clearly shows that the maximum stress occurs in the centre of the sample, in the area below the load point, although a significant portion of the stress occurs along the edges of the sample above the supports. Such stress above the support occurs only if the sample is simple supported, which can result in delamination. Delamination above the support occurs due to a weak glue line and the deformation caused by peeling stress (Sokolinsky 2003). In this research, a rigid core and rigid polyurethane resin was used and, as such, there was no delamination. Due to the fact that the values of edge stress are different for different support types, and because the maximum stress occurs below the load point, further analysis of stress and strain distribution was based only on the values in the centre of sample.

In the first layer (veneer), it is evident that the Von Mises stress is almost identical for both cases, when the load direction is parallel or perpendicular to the grain direction, and that is valid only for the model SP0, while these differences sharply increase and reach their maximum in the model SP3.5 (Fig. 3). These differences primarily occur due to the stress increasing in the *x* direction and partially in the *y* direction, while other values are relatively small (Tab. 3). However, it is very interesting to compare the absolute values of normal stress in *y* with the normal stress in the *z* direction, particularly in cases when the load direction is parallel to the grain direction. It is evident that the stress values in the *z* direction are even higher to those in the *y* direction, which certainly suggests the great importance of the analysis of normal stress in transverse direction in the veneer.

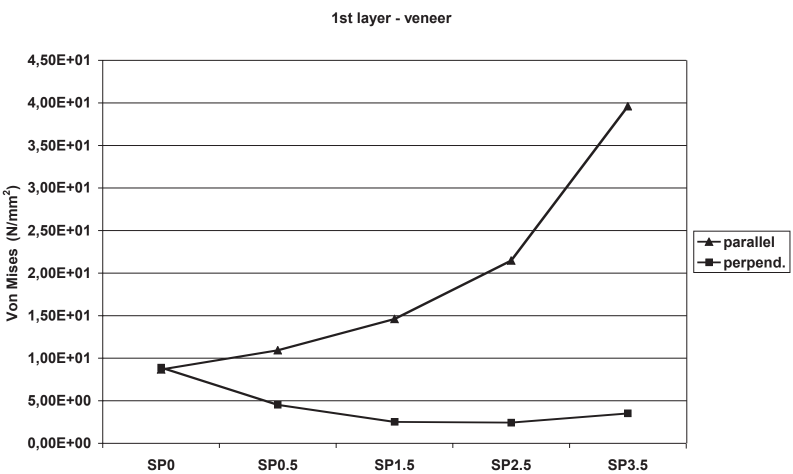

Fig. 3: Influence of variation of veneer thickness ratio on Von Mises stress in the first layer of sandwich panels

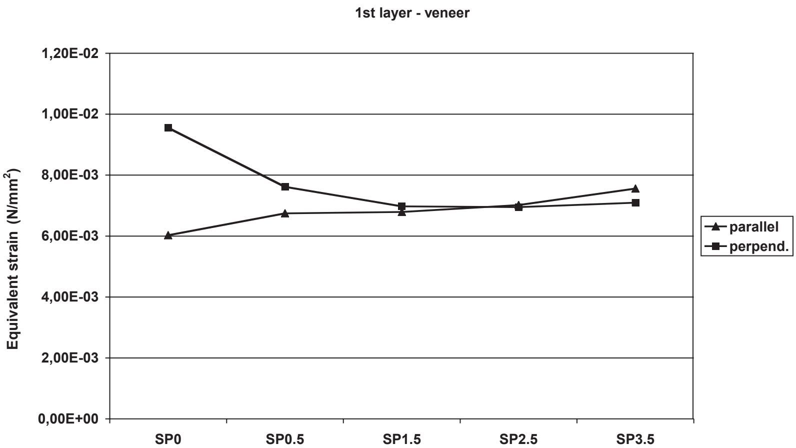

Fig. 4: Influence of variation of veneer thickness ratio on equivalent strain in the first layer of sandwich panels

Tab. 3: Stress components in the first layer (veneer) of sandwich panel

Parallel (N/mm^2)						
1st layer	SIG X	SIG Y	SIG Z	TAU XY	TAU XZ	TAU YZ
SP0	8.49E+00	6.46E-01	-8.11E-01	-1.81E-01	-1.51E-01	1.30E-01
SP0.5	1.06E+01	5.03E-01	-9.36E-01	-1.58E-01	-1.55E-01	1.40E-01
SP1.5	1.43E+01	4.50E-01	-9.08E-01	-8.74E-02	-1.72E-01	1.43E-01
SP2.5	2.13E+01	6.75E-01	-8.63E-01	-4.14E-02	-1.91E-01	1.49E-01
SP3.5	3.99E+01	1.41E+00	-7.46E-01	1.61E-02	-2.14E-01	1.55E-01
Perpendicular (N/mm^2)						
SP0	9.13E+00	1.28E+00	-5.28E-01	1.29E-01	-1.81E-01	1.42E-01
SP0.5	4.39E+00	1.09E+00	-7.63E-01	4.81E-02	-1.56E-01	1.35E-01
SP1.5	1.87E+00	1.21E+00	-8.90E-01	-2.56E-02	-1.72E-01	1.41E-01
SP2.5	1.16E+00	1.71E+00	-9.27E-01	-6.75E-02	-1.91E-01	1.49E-01
SP3.5	8.62E-01	3.07E+00	-9.44E-01	-1.15E-01	-2.12E-01	1.60E-01

SIG X, SIG Y, SIG Z – normal stress in the –x, -y , -z direction, respectively
TAU XY, TAU XZ, TAU YZ – shear stress in the –xy, -xz, -yz plane, respectively

Tab. 4: Strain components in the first layer (veneer) of sandwich panel

Parallel						
1st layer	EPSX	EPSY	EPSZ	GMXY	GMXZ	GMYZ
SP0	6.22E-04	5.07E-04	-7.47E-03	-1.71E-04	3.08E-03	-3.65E-03
SP0.5	7.89E-04	3.41E-04	-8.57E-03	-1.49E-04	3.33E-03	-3.73E-03
SP1.5	1.06E-03	1.48E-04	-8.44E-03	-8.25E-05	3.41E-03	-4.11E-03
SP2.5	1.56E-03	7.04E-05	-8.35E-03	-3.91E-05	3.56E-03	-4.56E-03
SP3.5	2.88E-03	-1.01E-05	-8.18E-03	1.52E-05	3.73E-03	-5.07E-03
Perpendicular						
SP0	8.12E-03	-2.29E-04	-7.47E-03	1.22E-04	3.44E-03	-4.27E-03
SP0.5	4.05E-03	-5.90E-05	-8.00E-03	4.54E-05	3.24E-03	-3.69E-03
SP1.5	1.88E-03	4.76E-05	-8.30E-03	-2.41E-05	3.39E-03	-4.09E-03
SP2.5	1.25E-03	1.12E-04	-8.41E-03	-6.36E-05	3.57E-03	-4.57E-03
SP3.5	9.40E-04	2.23E-04	-8.51E-03	-1.09E-04	3.79E-03	-5.10E-03

EPSX, EPSY, EPSZ – normal strain in the –x, -y , -z direction, respectively
GMXY, GMXZ, GMYZ – shear strain in the –xy, -xz, -yz plane, respectively

The influence of variation of the veneer thickness ratio on equivalent strain in the first layer is shown in Fig. 4. A similar trend line is present in all plywood layers, only with proportionally lower values.

The significant difference in strains, according to the load direction, occurs primarily in the model SP0 (0.0060 parallel; 0.0096 perpendicular), while in other models this difference is proportionately reduced or equalized. (In the trend line of stress, this trend was opposite and the smallest difference was for the SP0 and the highest for the SP3.5). The shape of this trend line is the result of orthotropic properties of plywood, in which its strength is much greater in the direction of length than width. Therefore, the differences in strain rise with increase of the veneer thickness ratio. The decrease of differences in veneer thickness ratios also decreases the difference in strain, in respect to the load direction.

In analysing the strain components it is evident that the highest strains are present in the *z* direction (Tab. 4), although under such load the highest strain is present in the *x* direction. This is the result of great differences in elastic properties of beech in the longitudinal direction, 13700 N/mm^2, and in the radial direction, 2240 N/mm^2. From such strain ratio it is also evident that the strain values in transverse direction are not only important for the core but they are also very important components in analysing the thin face layers, i.e. veneers.

In analysing the stress in the second layer, an exceptional increase in the value of stress from SP0 (7.58 N/mm^2) to SP0.5 (49.35 N/mm^2) was observed, following by rapid decrease from SP0.5 to SP1.5 (2/25 N/mm^2). These changes occur only if the load direction is perpendicular to the grain direction (Fig. 5). The high stress value in the model SP0.5, in comparison to the model SP0, is the consequence of two different factors: veneer thickness and veneer orientation. In the model SP0 the second layer (veneer) had a thickness of 1.5 mm and the load direction was perpendicular to its grain direction, while in the SP0.5 model both factors were altered. This means that in the model SP0.5 the load direction was parallel to the grain direction, and its thickness was reduced to only 0.5mm. However, with the next thickness ratio, this stress was markedly reduced, exclusively as a result in the change of veneer thickness. The veneer thickness was increased threefold, while its orientation has remained the same. Further reduces in stress were also the result of the thickness change.

In the second layer the highest values of stress components are present, primarily the normal stress in the *x* direction, which for the SP0.5 model was 4.99 N/mm^2 in the direction perpendicular to the grain. Other values of normal stress were markedly lower: 1.84 N/mm^2 in the *y* direction and 0.67 N/mm^2 in the *z* direction. For shear stress, the most pronounced component was in the *yz* plane: 0.10 N/mm^2, which is several times higher than other components of shear stress. Although the shear stress is relatively low, in comparison to normal stress, it also has a high influence on the value of strain components.

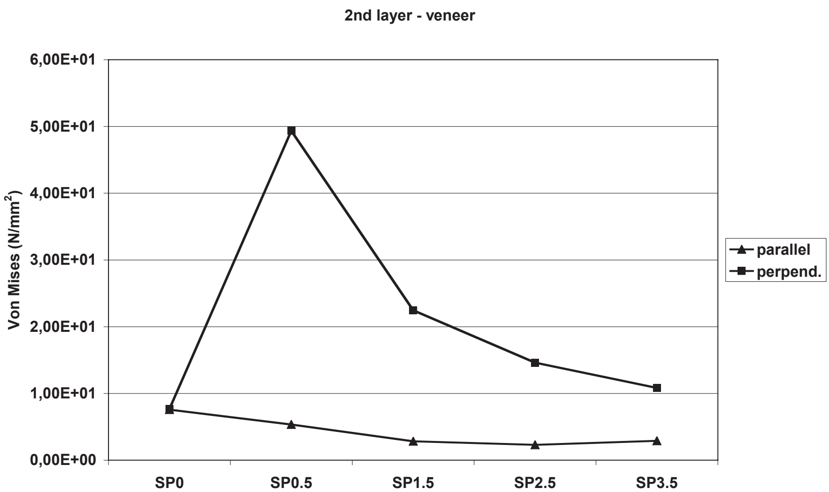

Fig. 5: Influence of veneer thickness ratio on Von Mises stress in the second layer of sandwich panels

In the third layer the stress curves are partially similar to those in the first layer, which is the result of the same veneer orientation. With variation of the veneer thickness ratio, the same curve formation is present (Fig. 6) for both load directions. Only the total amounts of stress are significantly smaller, especially in the direction parallel to the grain. This is particularly true for the model SP3.5, because the position of veneer (third layer) is nearer the neutral axis where the values of normal stress are commonly lower. As a result, the normal stress in the *x* direction decreases from 39.9 N/mm^2 in the first layer to 26.1 N/mm^2 in the third layer. The majority of other components has a lower stress as well, their difference is only smaller in comparison to the stress value in the first layer, unlike the normal stress in the *z* direction and the shear stress in the *xy* plane, where absolute values are somewhat higher than in the first layer.

The stress distribution in the fourth layer (the core) is characterized by a high increase of stress value in a range from model SP0 (1.0618) to model SP0.5 (1.2277), and that only in the cases when the load direction is parallel to the grain direction (Fig. 7). Such change with a high stress increase indicates that even a relative small relief of load on the faces leads to a great stress increase in the core in its transverse direction.

The other stress components in the core have lower value and no single component has a great influence on Von Mises stress value. It is an opposite to veneers where normal stress in the *x* layer dominates, either due to the structural position of the veneer sheets or due to their elastic properties.

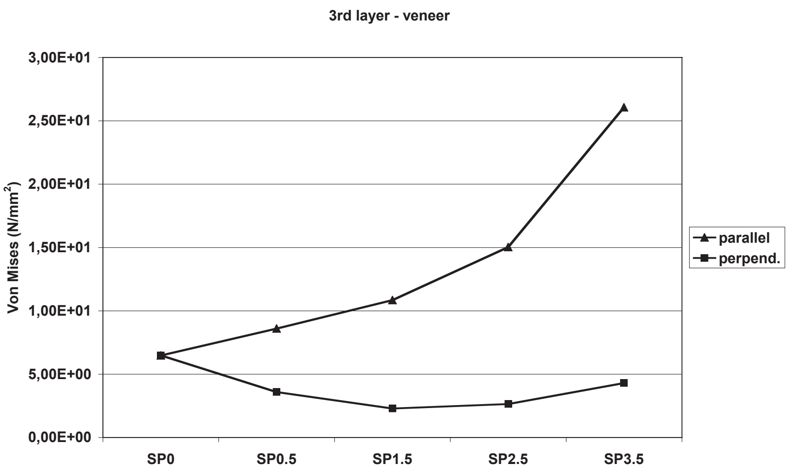

Fig. 6: Influence of veneer thickness ratio on Von Mises stress in the third layer of sandwich panels

Lower values of stress in the core are the result of its lower elastic properties and its positioning near the neutral axis. Therefore the core is mainly subjected to the transverse stress, both normal and shear stresses (Zenkret 1997). This is evident from the analyses of individual components of stress in which a significant increase of normal stress in the *z* direction and shear stress in the *xz* plane are observed. Normal stress in the *z* direction in the core ranges from 1.28 N/mm^2 to 1.50 N/mm^2, while the same stress in the second layer ranges from 0.57 to 0.94 N/mm^2 and in the first layer from 0.53 to 0.94 N/mm^2.

The increase of shear stress relates to stress in the *xz* plane, which in the core ranges from 0.43 to 0.49 N/mm^2, while in the first layer this ranges from 0.15 to 0.21 N/mm^2 and in the second layer from 0.60 to 0.71 N/mm^2.

The form of the stress trend lines for the core has a different form of the trend lines for the veneers. The main reason is that the core has isotropic properties and different elastic behaviour under the load. The form of shear trend lines for the core is almost identical to its form of stress trend line.

According to the conducted research it is evident that the variation of veneer thickness ratio in plywood has a great influence on mechanical properties of the sandwich panel.

However, by analysing the literature, it is possible to presume that the variation of the veneer grain angle in plywood has also a great influence on bending properties of sandwich panels, which should be the subject of future research.

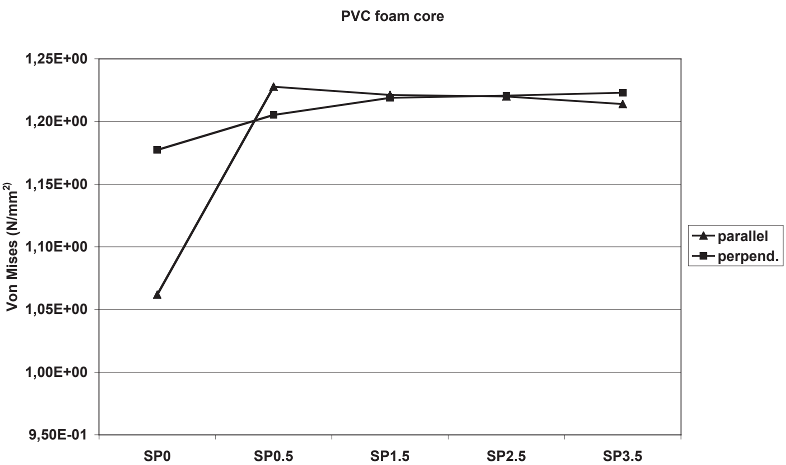

Fig. 7: Influence of veneer thickness ratio to the Von Mises stress in the core of sandwich panels

CONCLUSION

Based on experimental results of bending properties of sandwich panels and on results obtained using the 3D finite element analysis it is possible to draw the following conclusions:

- The variation of the veneer thickness ratio in plywood has a significant influence on the bending properties of sandwich panels. These relations have the form of a second-order polynomial, commonly.

- The highest values of the Von Mises stress occur when the veneer thickness ratio, with the grain direction parallel to the load direction, is the smallest. The highest value of Von Mises stress (39.6 N/mm^2) has occurred in the first layer of the sandwich panel SP3.5, parallel to the grain direction. When the load direction was perpendicular to the grain direction of the sandwich panel, the highest value of Von Mises stress (49.4 N/mm^2) has occurred in the second layer of the sandwich panel SP0.5.

- The variation of the veneer thickness ratio in the plywood has a significant influence on the stiffness of the sandwich panel. Stiffness can be increased by increasing the thickness ratio of the parallel oriented veneer sheets.

- Based on the analysis of all six components of the stress distribution in the 3D system, a significant amount of the stress value in the transverse direction was determined, both for the normal and the shear stress, and in each layer of the sandwich panel, i.e. in all veneer sheets and in the core.

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