The Stiffness of One-Sided, Asymmetrically Veneered Composites

Sylwia Olenska,[a,c,]* Jerzy Smardzewski,[b] and Piotr Beer [c]

The goal of the study was to analyse of the stiffness of one-sided, asymmetrical veneered boards by investigating the influence of glue type and board thickness on deflection and stress distribution on each composite layer. A specially designed stand that measured the whole area of the board was used to empirically measure the asymmetrically veneered elements. The theoretical measurements were taken using the Finite Elements Method in the *Autodesk Mechanical Simulation* 2015® program. All elements of composites including veneer (beech), glue-line (polyisocyanate and poly (vinyl acetate)), and the wood-based panel were simulated as elastic materials.

Keywords: Wood composites; Veneering; Stress analysis; Deflections

*Contact information: a: Polish Chamber of Commerce of Furniture Manufacturers, et al. Stanów Zjednoczonych 51, 04-028 Warsaw; b: Furniture Department, Faculty of Wood Technology, Poznań University of Life Sciences, ul. Wojska Polskiego 42, 60-628 Poznań c: Department of Technology and Enterpreneurship in the Furniture Industry, Faculty of Wood Technology, Warsaw University of Life Sciences, ul. Nowoursynowska 159, 02-776 Warsaw; *Corresponding author: sylwia.olenska@gmail.com*

INTRODUCTION

The furniture industry is a very important sector of the economy for many countries such as China, Germany, Italy, Poland, and the USA. Particularly in Poland, the furniture industry is a strategic sector and ranks in fourth place among furniture exporters in the world. The furniture industry must be advanced with innovative technologies. One promising example is asymmetrical veneering of flat free fixed furniture parts such as doors and shelves. Such veneering is now done intuitively, and it has a large risk of failure. Even though this technological problem has existed for many years, it has appeared in literature only recently. This information underlines the craftsmanship of carpenters who perform asymmetrical veneering of elements that do not deform under the influence of changing environmental conditions and everyday use (Hayward 1983). Because the described process is performed manually, it does not meet the current requirements of mass production.

Asymmetrical veneering is mentioned in handbooks and could be applied to manufacturing furniture elements that are well-suited for the whole furniture construction and are of a thickness greater than 16 mm (Scheibert 1958). Without asymmetrical veneering, the panel balance could be disturbed, and one could encounter serious panel warpage either soon after manufacture or upon equilibration in the service environment (Moslemi 1974). Asymmetrical veneering is applied to finish plywood (Feirer 1979) or to finish panels with a material such as aluminium foil that does not change its properties or dimensions under normal conditions (Negri *et al*. 2009).

The elements analysed in the presented studies are composites assembled from several parts. There are two types of modelled composites: (1) boards veneered asymmetrically on one side, where the composite is assembled from three parts including natural veneer, glue-line, and a wood-based panel; and (2) boards veneered asymmetrically on both sides, where the composite is assembled from five parts including natural veneer kind 1, glue-line, a wood-based panel, glue-line, and natural veneer kind 2.

Numerical simulations for wood-based panels veneered asymmetrically on both sides have two basic goals. First, they check the possibility of mechanical properties of the glue-line having an influence on the level of deflections of boards veneered asymmetrically. Second, they perform theoretical analyses of deflections is similar to the result of real measurements. The positive result would be the basis for the possibility of predicting the level of panel deflections before its veneering.

There are three popular defined methods of numerical modelling of elements (Łodygowski and Kąkol 2003). The Boundary Element Method (BEM) is one of the most effective simulation methods. In theory, it is boarded to discretization of boundary conditions of elements. However, it is a method that is usually uneconomical because data processing is not time-efficient, and it requires a computer with high memory. The Discrete Element Method (DEM) is a numerical method used for modelling large quantities of elements in a condition of free movement; the method is often used in modelling grains, for example. The Finite Element Method (FEM) is a numerical method based on dividing elements to finish parts to evaluate results by using appropriate functions. Choosing an appropriate method of simulation needs preliminary analysis of the modelled material for accurate results.

The aim of the study was to model and carry out numerical analysis of the stiffness and normal stresses of one-sided asymmetrical veneered boards and investigate the influence of glue type and board thickness on deflection and stress distribution in each composite layer.

EXPERIMENTAL

Methods

The studies analysed deflections of a one-side veneered board. The structure of a typical board of this type is presented in Fig. 1. Studies on the practical possibility of asymmetrical veneering were done on a projected measurement stand (Fig. 2).

The stand defines a reference virtual plane (Fig. 2, (1)). This plane is created with four pegs, three of which have a constant height of 30 mm (3, 4, 5). The fourth peg is adjustable (6) to the shape of the panel. Because the panel is adjustable, it is in contact with all four pegs. The force is axially positioned with pegs, and the panels are always placed equally in position to each peg. The position of the panels is settled with three fixed blocks (7, 8, 9). The visible surface of the strip (10) forms the reference surface. The strip is placed with three blocks (8, 9, 11). The distance between the reference virtual plane and reference surface of the strip is constant, and this is where the measured board is placed. The geometry is measured in five areas (2), five times in each area (3 mm gap) with a depth gauge. Its precision is 0.01 mm, and measurement error is 0.02 mm.

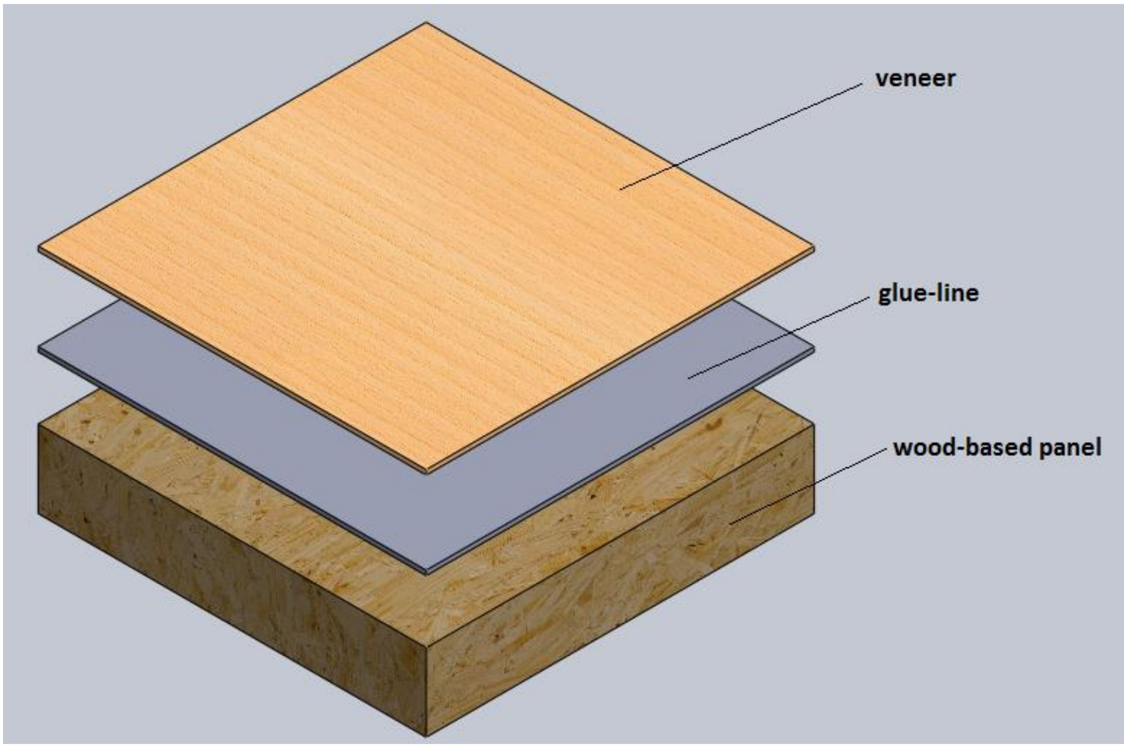

Fig. 1. The structure of a one-sided, asymmetrically veneered panel (Oleńska *et al.* 2012)

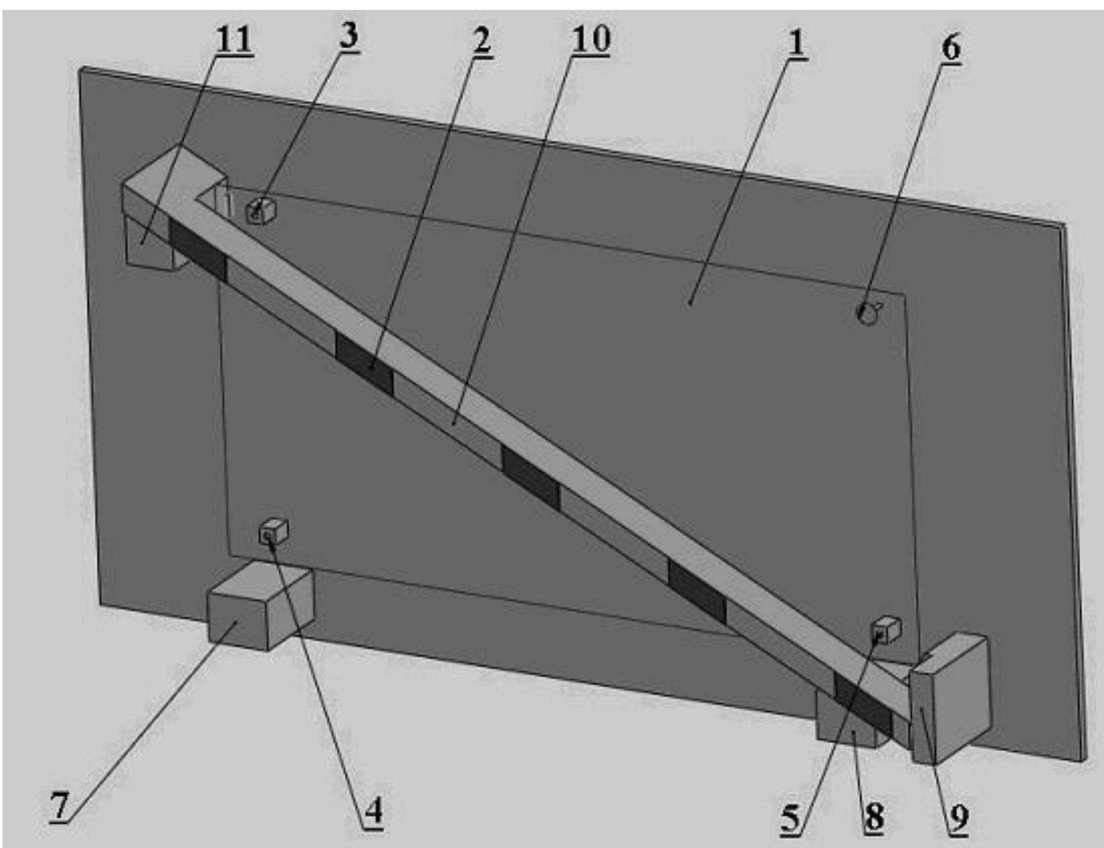

Fig. 2. The measurement stand (see description in the text bellow) (Oleńska *et al.* 2014)

Numerical Modeling

The theoretical values corresponding to the asymmetrically veneered panel deflections were calculated using the Finite Elements Method. Simulations were carried out for boards veneered asymmetrically on one side because it was necessary to determine the properties of the natural veneer, glue-line, and wood-based panel.

To compare theoretical results with the measurements performed for real elements, studies were made for boards veneered using beech (*Fagus sylvatica*), using two types of glue, standard poly(vinyl acetate) (PVaC) glue (which is used in veneering technology) and experimental polyisocyanate (PMDI) glue, produced by PCC-Prodex, Warsaw, Poland. In the presented studies, there are board analyses for two thicknesses of 10 mm and 18 mm. These are the most popular wood-based panels used for furniture production in Poland. The analysis of the two thicknesses examined the influence of the composite thickness and its deflection.

The first modelled part was beech veneer. The studies assumed that the standard thickness of veneered panels sold on the market was 0.6 mm. Because of the hygroscopic properties of wood, modelling analysis covered all changes of material properties that are affected by changing humidity. The assumed humidity change was from 5.9% to 16.3%, which is why studies determined hygroexpansion factors. This range shows the wood humidity changes that can exist in various climate conditions. Wood is an anisotropic material, so when modelling the veneer, it is defined as an orthotropic material (material that has different properties in three analysed directions).

Hook's law describes the relationship between the deflection state and the stress of orthotropic substance, and there is a susceptibility matrix which includes twelve material constants. Because of their symmetry in terms of the main diagonal, there are relations as follows,

$$\frac{\vartheta_{ij}}{E_i} = \frac{\vartheta_{ji}}{E_j}, where\ i, j = X, Y, Z\ or\ L, R, T \tag{1}$$

where L, R, and T are the anatomical wood directions along the fibres, radial and tangential, respectively.

Thus, the number of independent parts of the susceptibility matrix of beech wood and wood-based panel is reduced to nine (Table 1). The matrix elements have the following relationships:

$$S_{11} = \frac{1}{E_L};\ S_{22} = \frac{1}{E_R};\ S_{33} = \frac{1}{E_T} \tag{2}$$

$$S_{44} = \frac{1}{G_{RT}};\ S_{55} = \frac{1}{G_{TL}};\ S_{66} = \frac{1}{G_{LR}} \tag{3}$$

$$S_{12} = -\frac{\vartheta_{RL}}{E_R},\ S_{21} = -\frac{\vartheta_{LR}}{E_L}; \tag{4}$$

$$S_{13} = -\frac{\vartheta_{TL}}{E_T};\ S_{31} = -\frac{\vartheta_{LT}}{E_L}, \tag{5}$$

$$S_{23} = -\frac{\vartheta_{TR}}{E_T};\ S_{32} = -\frac{\vartheta_{RT}}{E_R}, \tag{6}$$

Hence,

$$\begin{bmatrix} \varepsilon_L \\ \varepsilon_R \\ \varepsilon_T \\ \gamma_{RT} \\ \gamma_{TL} \\ \gamma_{LR} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{bmatrix} \begin{bmatrix} \sigma_L \\ \sigma_R \\ \sigma_T \\ \tau_{RT} \\ \tau_{TL} \\ \tau_{LR} \end{bmatrix}. \tag{7}$$

For the isotropic substance, the glue-line, there exist only two matrix parts between which there are relations (Smardzewski 2015):

$$E = 2G(1+\vartheta). \tag{8}$$

The only composite elements where humidity-changing properties were not taken into account during the studies were modelled glue-lines. The preliminary studies did not include all glue-line properties that depend on changing environment conditions. The most important thing which was not taken into account in the present studies was the possible difference in glue-line thickness after the gelling process.

Glues react in various ways in areas of higher humidity and temperature. The glue-line has a different thickness after gelling because of this. In simulations, the established thickness of poly(acetate)vinyl glue-line is 0.1 mm, and the thickness of polyisocyanate glue-line with catalyst is 0.2 mm. The thickness of a PMDI glue-line is higher because the glue becomes foamy during gelling process, increasing its volume.

Studies in Austria and Switzerland concentrated on determining the differences in elasticity between various glue-lines. Scientists have underlined that the properties of the glue-line which connects wood and/or wood-based elements are mainly determined by the properties of the wood fibres (Konnerth and Gindl 2006), and the deflections they cause are the effect of interphase influence (Gindl *et al*. 2005). Unfortunately, there is not a description of the methodology used in studies of glue-line properties after its connection with wood elements. The methodology used is based on studies of thick samples of 0.05 to 0.1 mm thickness, depending on glue type (Konnerth *et al*. 2006).

Studies were done for a sample of popular three-layer wood-based panels. The base analysed the parallel arrangement of internal and external layers chips, allowing to describe the board during modelling as a material of stable properties. Factor values were characterised by a mean value of all layers. The veneer, exactly the same as the wood-based panel, was modelled as an orthotropic material where the properties depended on the direction of the chip arrangement in the element.

The wood-based panel is the element whose properties depend on each part that the board consists of. Because the main part of board is wood, it is determined as a hygroscopic material. However, studies so far around the world have only concentrated on analysing the changing board density due to humidity. It was assumed there was a changing density of board, with stable strength properties. The properties of all elements of composites used in simulations are presented in Table 1.

For modelling stress that is the effect of the shrinkage of one-sided sticky veneer, the unit shrinkage for each anatomical direction of beech wood was counted. It was assumed that in the hygroscopic range (from 0% up to 30%), linear shrinkages are S_L= 0.5%, S_R= 4%, and S_T= 8% along the fibres, radial, and tangential, respectively. The unit shrinkage for 1 % of wood humidity change is then $S_{L/i}$= 0.0166%, $S_{R/i}$= 0.133%, $S_{T/i}$= 0.266%.

Table. 1. Physical-Mechanical Properties of Materials (Study Based on Papadopoulos *et al*. 2002; Konnerth and Gindl 2006; Klausler *et al*. 2013; Ożyhar 2013; Oleńska 2015)

Properties	Unit	Materials					
		Beech 5.9% Moisture Content	Beech 16.3% Moisture Content	Particle Board 8 mm	Particle Board 18 mm	Glue-line PMDI-1	Glue-line PVAC
$E_{L(X)}$	MPa	12020	9200	2930	2530		
$E_{R(Y)}$		1800	1240	2930	2530		
$E_{T(Z)}$		810	530	310	260		
E						2409	2410
$G_{LR(XY)}$		1645	1073	490	430		
$G_{LT(XZ)}$		1083	707	490	430		
$G_{RT(YZ)}$		471	307	155	145		
G							
$n_{LR(XY)}$		0.04	0.04	0.035	0.035	0.31	0.38
$n_{LT(XZ)}$		0.04	0.05	0.35	0.35		
$n_{RT(YZ)}$		0.24	0.36	0.27	0.27		
ρ	kg/m^3	655	662	820	650	1150	1110

Before veneering, the absolute humidity of wood-based panels was 5.9%, and the beech veneer had 16.3% of absolute humidity. After veneering, the samples were conditioned until the whole composite reached 5.9% absolute humidity. The absolute humidity changes in the veneer at the stage of 10.4%, was used to determined its total shrinkage S_L, S_R, S_T, which are respective to linear deflections e_L = 0.00172, e_R = 0.01383, and e_T = 0.02766. For the overall dimensions of the studied boards (Fig. 3a), the shortening of veneer in each orthotropic direction was: jL = 0.774, jR = 3.1122, jT = 6.2244 [mm]. The established values of deflections were used in the numerical model (Fig. 3b).

The modelled elements were wood-based panels of 8 mm and 18 mm thickness, veneered using natural beech veneer with a thickness of 0.6 mm. The total thickness of the PVaC glue-line was 0.1 mm, and of PMDI glue-line was 0.2 mm after gelling. Anyway, the application of the glues was the same- 150g/m^2. PVaC glue-line during gelling misses the water so the final thickness is lower. In the gelling process of PMDI the glue reacts with the water and foams so the thickness of the final glue-line is higher. The total thickness of the formed, asymmetrical composite was 8.7 mm and 18.7 mm when using the PVaC glue-line, and 8.8 mm and 18.8 mm when using the PMDI glue-line (Fig. 1a). For modelling, iso- and orthotropic, eight-noded finished brick-type elements were chosen.

The veneer and wood-based panels were assigned the orthotropic properties, and the glue-line was assigned isotropic properties (Table 1). The boards were propped freely along the shorter edge, taking one freedom degree in a vertical direction. The stresses were constrained by assigning negative strains e_L, e_R, e_T to the veneer layer (Eq. 7). While modelling the sandwich panels, two thicknesses of boards and two types of glue-lines: PMDI and PVaC were used. Together, four models were determined, assembled with a minimum of 229063 nodes and with a minimum of 181808 elements. The calculations were made using the Finite Elements Method in the computer program Autodesk Mechanical Simulation 2015® (Autodesk Inc., San Rafael, California, USA).

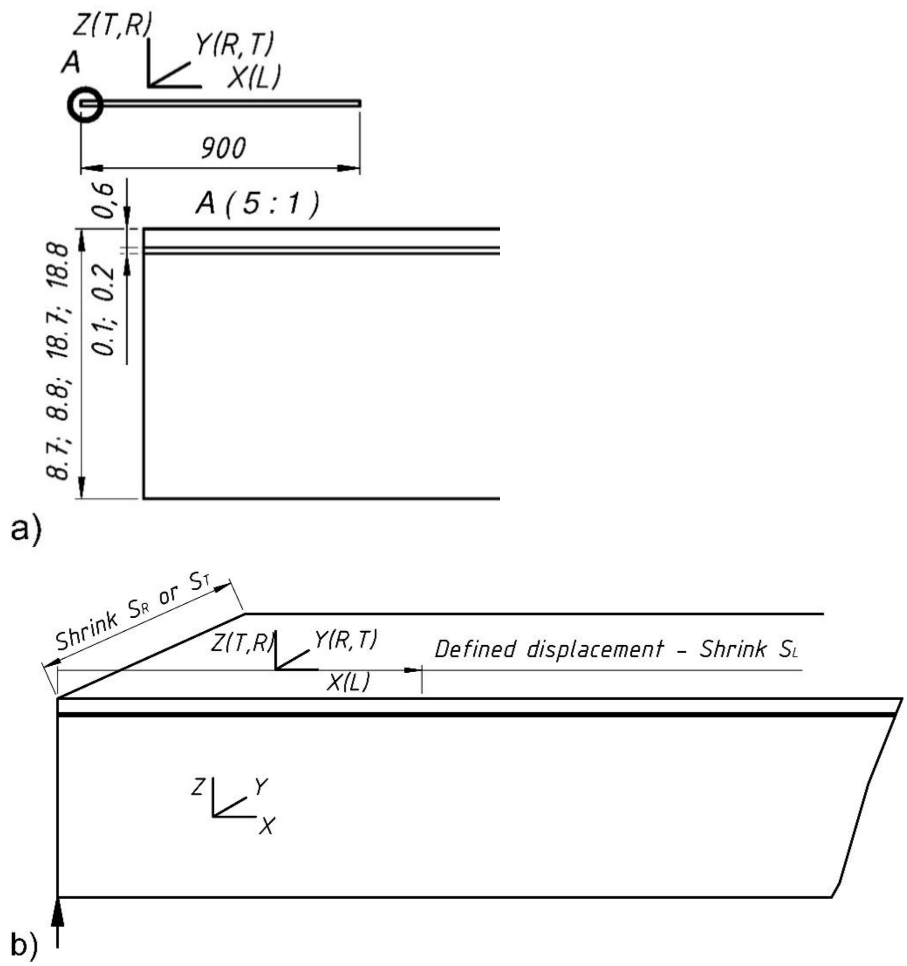

Fig. 3. Numerical model of wood-based sandwich panel: (a) geometry; (b) defined shrinks (all units are in mm)

RESULTS AND DISCUSSION

Experimental Investigations

Empirical measurements of the board showed the highest deflections in the middle of the board. The value of deflection was 1.1 mm, which is unacceptable in the industrial production of furniture elements. The asymmetrically veneered board with a thickness of 8 mm with PMDI glue (Fig. 5) had the highest deflections in the median part of the composite. The highest deflection of the board after veneering was the same as the board veneered with PVaC glue-line (Fig. 4). In fact, in the case of 8 mm-boards, the glue-line had little influence on deflections because of the unstable, thick wood-based panel. At the same time, observed stresses were 33% lower than a board veneered using a standard PVaC glue-line.

In a board with a thickness of 18 mm, veneered with using poly(vinyl acetate) glue (Fig. 6), empirical studies showed that deflections in the 18 mm-thick element were mostly the same as a board with a thickness of 8 mm. It is noticeable that the level of deflections of a board of this thickness was 1.21 mm.

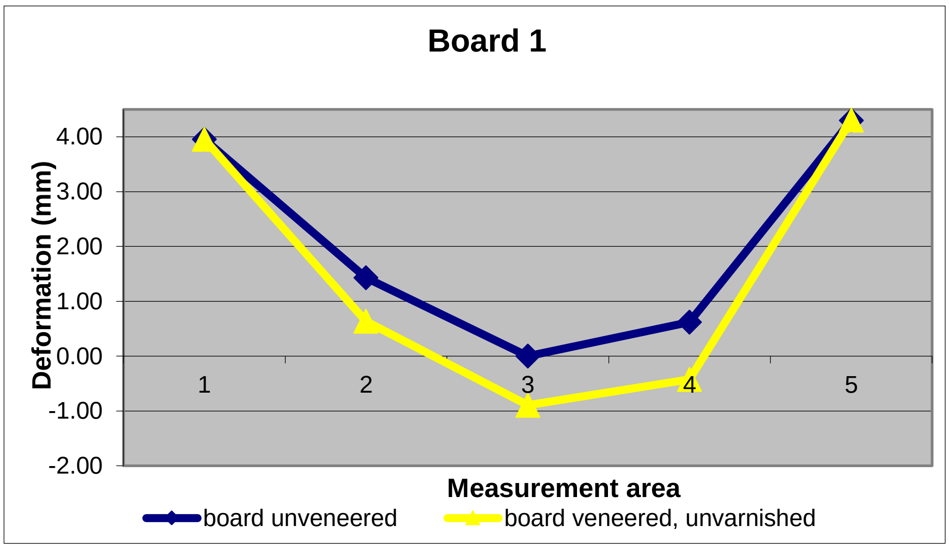

Fig. 4. Deflections of a board with a thickness of 8 mm, veneered with using PVaC glue

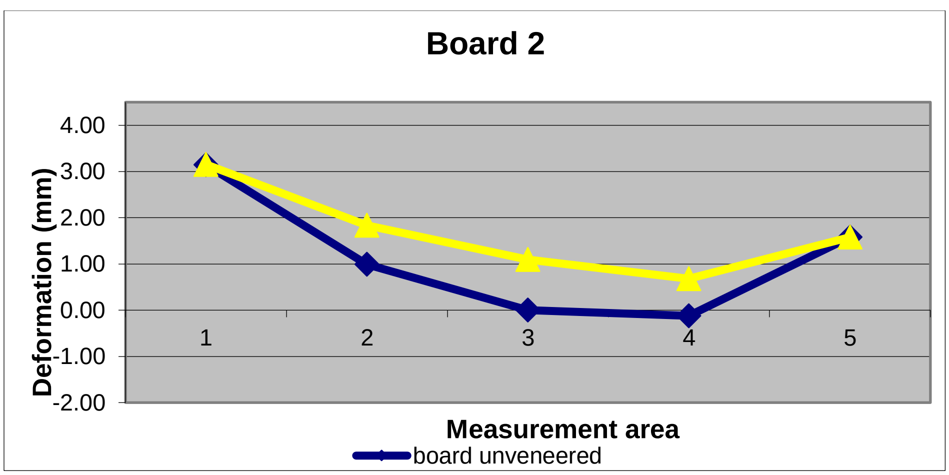

Fig. 5. Deflections of board with a thickness of 8 mm, veneered with using PMDI glue

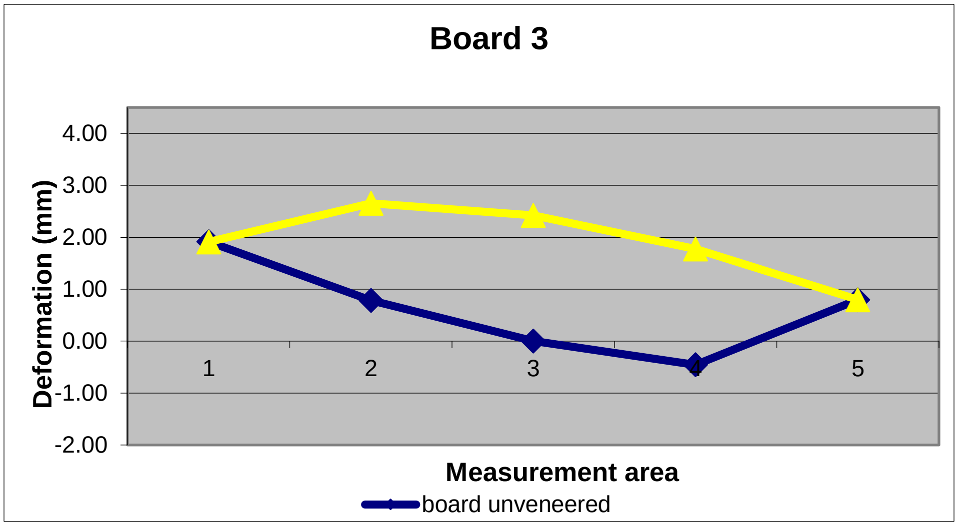

Fig. 6. Deflections of a board with a thickness of 18 mm, veneered with using PVaC glue

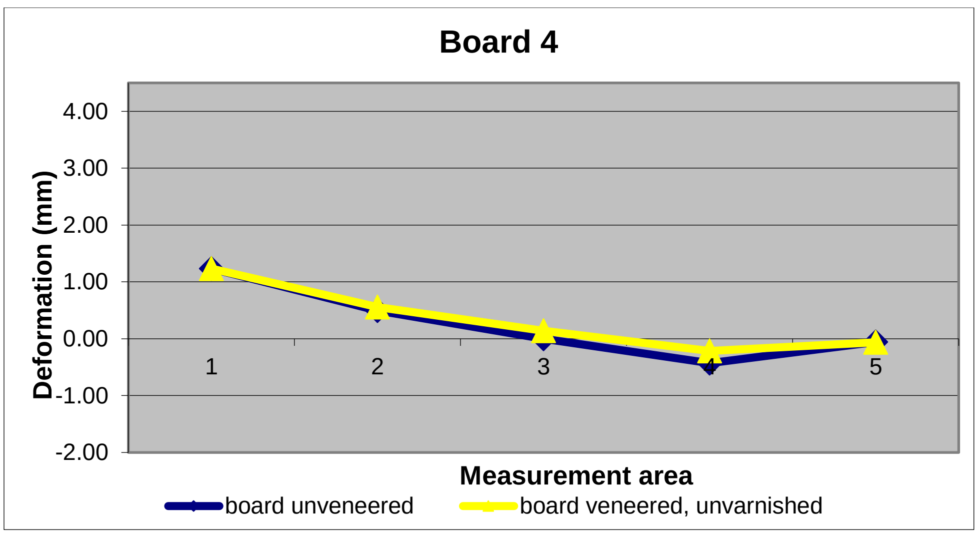

Fig. 7. Deflections of a board with a thickness of 18 mm, veneered using PMDI glue (Oleńska 2015)

For the board veneered using PMDI glue (Fig. 7), the maximum deflections were relatively lower than a board with a thickness of 8 mm, and they are lower than in a composite veneered using PVaC glue. As a result, maximum deflections in the composite had a minimum degree of only up to 0.1 mm. This result showed that the type of glue used has an influence on deflections in the sandwich panel, though only in the case of composites where the base is a panel with an industrially stable shape.

Numerical Modeling

Figure 8 presents deflections for a symmetrical half of sandwich boards. Due to similar elastic properties of PMDI and PVaC glues, the type of glue used did not have an influence on the stiffness of veneered furniture boards. However, the thickness of the wood-based panel had a noticeable influence. Composites with a thickness of 18.7 mm and 18.8 mm had 260% higher stiffness than composites of 8.7 mm and 8.8 mm thickness.

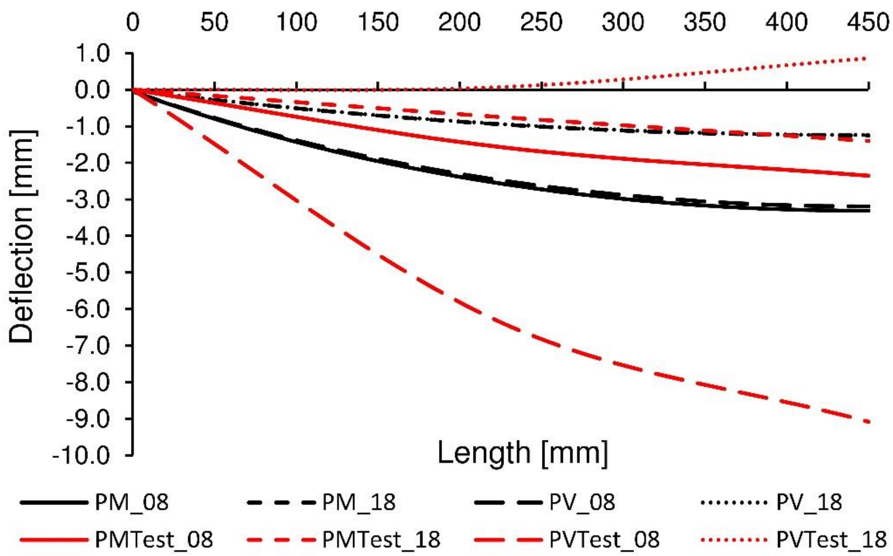

Fig. 8. Deflection of wood-based sandwich panels

Experimental studies confirmed the accepted compatibility of deflections only for boards with a thickness of 18 mm, veneered using PMDI resin. The difference in the results was 11.8%. For the remaining composites, the differences were 29% for boards with a thickness of 8.8 mm, veneered with PMDI resin, as well as 169% and 284% for boards with thicknesses of respectively 8.7 mm and 18.7 mm, veneered using PVaC glue.

There was a dramatic correspondence between veneer shrinkage and the growth of stresses close to the wood-based panel edge (Fig. 9). Particularly, relatively high normal stresses, from 0.012 MPa up to 0.042 MPa, existed in the lower layer of the wood-based panel of composites with a thickness of 8.8 mm and 8.7 mm, veneered using PMDI and PVaC resins. For composites with a thickness of 18.8 mm and 18.7 mm, the stresses were on the level from 0.005 MPa up to 0.020 MPa. The type of glue used for the analysed boards did not change the values of normal stresses in wood-based panel. Their value depended on the thickness of wood-based panel.

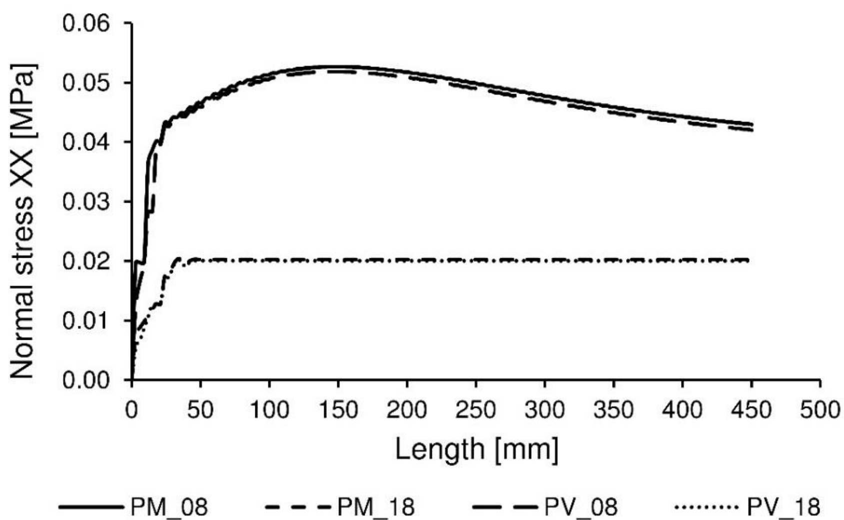

Fig. 9. Normal stresses in the lower layer of the particle board

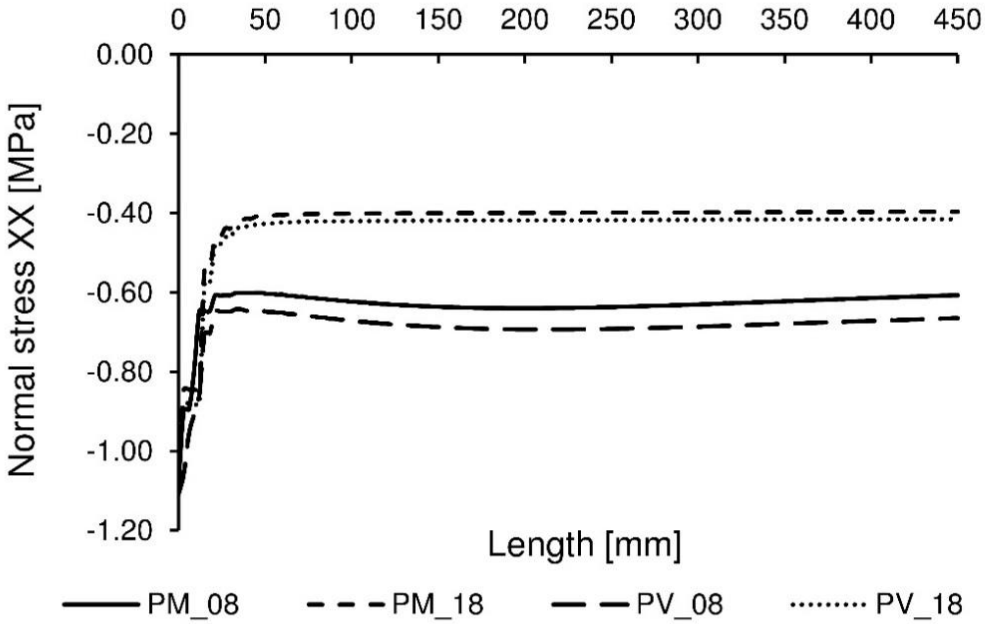

Fig. 10. Normal stresses in the lower layer of veneer

Higher compressive stresses were observed in the wood-based panel than in veneer (Fig. 10). Additionally, in this case, relatively higher normal stresses appeared on the veneer edge. In the lower veneer layers of composites with a thickness of 8.8 mm and 8.7 mm, veneered using PMDI resin, stresses were shaped from 1.10 MPa to 0.66 MPa. Half of these values of stresses were noted for veneers of composites with a thickness of 18.8 mm and 18.7 mm. In this case, the stresses values were on the level from 1.09 MPa to 0.41 MPa. Using PVaC glue for a composite with a thickness of 8.7 mm increased only slightly (substantially) the stresses in relation to the structure glued with using PMDI.

Figure 11 illustrates the course of stresses in lower layers of the glue-line. The highest normal stresses appeared in the glue-line edge. In the lower layers of composites of 8.8 mm and 8.7 mm, veneered respectively with PMDI and PVaC glue-lines, stresses shaped from 0.86 MPa to 0.63 MPa. The difference of the value of stresses in the glue-line was 0.055 MPa against the PVaC glue. For elements with a thickness of 18.8 mm and 18.7 mm, the stresses were mostly equal and were in the range of 0.81 MPa to 0.40 MPa. The difference of the value of stresses in the glue-line was 0.018 MPa against the PVaC glue.

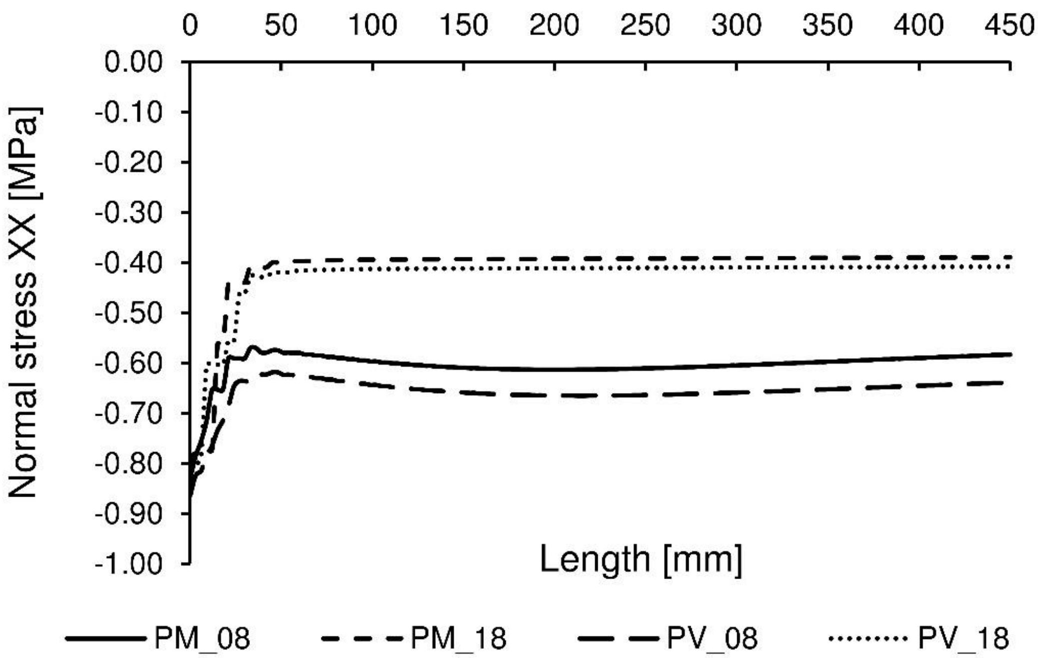

Fig. 11. Normal stresses in the lower layer of the glue-line

CONCLUSIONS

1. A comparison achieved using the Finite Element Method and empirical studies of samples show that the results from simulations did not always correlate with the level of deflections of real boards. The similar elastic properties of PMDI and PVaC glue-lines caused very similar stress distribution in veneer and in wood-based panels. These results are the effect of the assumptions made concerning the glue-line properties.
2. It is known that a glue-line is not supremely elastic, and its properties are better characterised with modelling it as a hyperplastic material. Such material does not deform in a linear way, and because of that it needs to have additional properties studied (for example viscoelasticity by creeping measurement (Rośkowicz 2009)). In the literature, there is no data that would allow the glue-line to be modelled in this way. Because of that, good compatibility of the calculation and measurements results was observed only in the case of deflections of composites with a thickness of 18.8 mm, glued with PMDI glue-line.
3. Numerical simulations made it possible to determine the composite part in which the maximum stresses are. This information enables the composite element that decides on the level of deflections to be determined.

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